CLIMATE-DRIVEN ASSET MANAGEMENT OF PUBLIC BUILDINGS: A MULTI-PERIOD MAINTENANCE PLANNING FRAMEWORK

by

Vithanapalpita K Rajeev J Ruparathna

M.A.Sc., The University of British Columbia, 2013
B.Sc. (Eng.), University of Moratuwa, 2008

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE COLLEGE OF GRADUATE STUDIES

(Civil Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Okanagan)

June 2017

The following individuals certify that they have read, and recommend to the College of Graduate Studies for acceptance, a thesis/dissertation entitled:

CLIMATE-DRIVEN ASSET MANAGEMENT OF PUBLIC BUILDINGS:

A MULTI-PERIOD MAINTENANCE PLANNING FRAMEWORK

submitted by Vithanapalpita K Rajeev J Ruparathna in partial fulfillment of the requirements of the degree of Doctor of Philosophy.

Dr. Kasun Hewage, School of Engineering: Civil Engineering
Supervisor

Dr. Rehan Sadiq, School of Engineering: Civil Engineering
Supervisory Committee Member

Dr. Sumi Siddiqa, School of Engineering: Civil Engineering
Supervisory Committee Member

Dr. Lukas Bichler, School of Engineering: Mechanical Engineering
University Examiner

Dr. Tamer El-Diraby, University of Toronto
External Examiner

Abstract

Reducing the greenhouse gas (GHG) emissions and shrinking the environmental footprint are priority themes of the Federal Sustainable Development Strategy of Canada. Public buildings account for the major portion of the corporate GHG footprint of public sector institutions. Improving the energy efficiency in buildings is vital in achieving the climate action targets pertaining to the public sector. According to Canadian Infrastructure Report Card, the physical condition of public buildings is expected to deteriorate in the future. In order to make the best use of the limited financial resources, hybrid building management plans which combine energy efficiency with physical condition improvement need to be developed. Building maintenance and retrofit plans are formulated for medium and long terms in the capital asset planning process. There is significant uncertainty associated with asset management decision making due to macro-economic variations such as technological advancements and new policies. At present, there are no pragmatic decision making methods that assist building asset management while incorporating future macro-economic changes. This research aims to bridge the aforementioned gap in literature by developing a multi-period asset management framework.

The overall objective of the proposed research is aimed at developing a decision support framework for small and medium scale municipalities in Canada to attain climate action targets of municipal buildings, while prolonging the service life of the building components. This research will help to identify, evaluate, and prioritize maintenance or repair or replacement strategies, and to develop a comprehensive multi-period life cycle asset management plan based on allocated funding, targeted sustainability performance and future macro-economic changes. The findings of this research will extend the current body of knowledge by incorporating potential future technological advancement and climate action targets into the asset management decision making. The proposed asset management decision support framework consists of a retrofit investment planning method, a level of service (LOS) index, life cycle costing (LCC) technique, and a risk based maintenance planning approach. This research is expected to assist at all decision making levels in public sector institutions related to building asset management, and thereby in achieving corporate climate action targets.

Preface

I, Rajeev Ruparathna, conceptualized and developed all the contents in this thesis under the supervision of Dr. Kasun Hewage. The third author of the articles from this research work, Dr. Rehan Sadiq, supervisory committee member, has reviewed all the manuscripts and provided critical feedback in the improvements. Five journal articles, which are currently published, accepted or under review, have been prepared directly from the research presented in this thesis. Two peer reviewed conference papers indirectly related to this research have also been published. Complete references of the aforementioned papers are listed below.

[J1] **Ruparathna, R.** Hewage, K., Sadiq, R. (2017) Economic analysis of building retrofits: An uncertainty based approach , *Energy and Buildings* 139: 395–406, doi: 10.1016/j.enbuild.2017.01.031

[J2] **Ruparathna, R.** Hewage, K., Sadiq, R. (2016) Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings, *Renewable and Sustainable Energy Reviews*. 53: 1032–1045,doi: 10.1016/j.rser.2015.09.084

[J3] **Ruparathna, R.** Hewage, K., Sadiq, R. (2017) Rethinking in investment planning in net zero emission buildings, to Clean Technologies.1-14, *and Environmental Policy*, doi:10.1007/s10098-017-1359-4

[J4] **Ruparathna, R.** Hewage, K., Sadiq, R. (2017) Asset Management of Buildings Infrastructure: A level of service (LOS) index for operational management, *Sustainable Cities and Society (In press)*

[J5] **Ruparathna, R.,** Hewage, K., Sadiq, R. (2017) Multi-period maintenance planning for public buildings: A risk based approach for climate conscious operation, *Journal of Cleaner Production*, (Submitted | Manuscript ID: JCLEPRO-D-17-02569)

[C1] **Ruparathna, R.,** Hewage, K., Sadiq, R. (2015) Improving the eco-efficiency of public buildings: A case study, Build LCA conference, Australian Life Cycle Assessment Society, Melbourne, Australia.

[C2] **Ruparathna, R.,** Hewage, K., Sadiq, R. (2015) Assessment of the Level of Service (LOS) of Public recreational center buildings: An uncertainty based approach, Canadian Society of Civil Engineers, International Construction Specialty Conference, Vancouver, BC.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AC	Alternating current
BMP	Best management practices
PV	Photovoltaic
TABS	Thermally activated building systems.
AIRR	Adjusted internal rate of return
BC	British Columbia
BIPVT	Building integrated photovoltaic/thermal
BPN	Back propagation artificial neural networks
BPI	Building performance indicator
BIM	Building information modelling
CAD	Canadian dollars
CO_{2eq}	Carbon dioxide equivalents
CHP	Combined heating and power
CPI	Component performance indicator
DC	Direct current
DG	Distributed generation
DSW	Dong, Shah, and Wong
ERV	Energy recovery ventilators.
EAC	Equivalent annual cost
ETRC	Existential technology research center.
FCI	Facility condition index
FM	Facilities management
FPE	Facility performance evaluation
FSE	Fuzzy synthetic evaluation
FV	Future value
GHGR	Greenhouse gas emissions reduction
GHG	Greenhouse gases
GDP	Gross domestic product
GCHP	Ground-coupled heat pumps.
HVAC	Heating, ventilation, and air conditioning.
IAQ	Indoor air quality
IRR	Internal rate of return
ISO	International Organization for Standardization
LEED	Leadership in Energy & Environmental Design
LCA	Lifecycle assessment
LCC	Life cycle cost
LCCA	Life cycle cost analysis
LED	Light emitting diode
LOS	Level of service
LOSI	Level of service index

MoM	Mean of maximum
MCS	Monte Carlo Simulation
MOO	Multi-objective optimization
NS	Net savings
NZEB	Net-zero emission buildings
NZEI	Net-zero emission investment
OM & R	Operation, maintenance, and repair costs
PI	Performance indicator
PC	Performance category
PP	Payback period
PJ	Peta joules
PV	Present value
SIR	Savings-to-investment ratio
SPI	System performance indicators
SSPCM	Shape-stabilized phase change material.
TBP	Total building performance
TPM	Transition probability matrix
TQA	Total quality assessment
USEPA	United States Environmental Protection Agency
VaR	Value at risk

.

Acknowledgements

I would like to express my heartfelt gratitude to Dr. Kasun Hewage for his immense support throughout my graduate studies. He had the faith in me to offer a graduate studies opportunity at the University of British Columbia. His immense support, wisdom, and advice have guided me in successfully completing my studies. I am forever grateful for the inspiration, motivation, and energy he provided, which influenced me in many ways not only in pursing my graduate studies but also beyond that. I will forever be in debt to him for his kindness.

I would like to thank Dr. Rehan Sadiq for his guidance for support. Despite his busy schedule, Dr. Sadiq always had time to discuss my research problems and to help in maturing my research. I am forever grateful to Dr. Rehan Sadiq for his guidance.

I would also like to thank my committee members, Dr. Sumi Siddiqa and Dr. Lukas Bichler. The advice and encouragement I received from them has helped me to improve the quality of this thesis. In addition, I would like to thank Dr. Soloman Tesfamariam, Dr. Abbas Milani, Mr. Bill Berry and Dr. Keith Culver, from whom I gained valuable knowledge and learned efficient techniques that I applied in my thesis. Moreover, I would like to acknowledge the School of Engineering and the administrative staff of the University of British Columbia Okanagan for their support.

The input from many external institutes and individuals was vital for successful completion of this study. I would like to thank Mr. Phil Hawkes of ForticBC, Mr. Blake Lavan and Mr. Chris Schimit of City of Penticton and Mr. Martin Johanson of City of Kelowna. His assistance helped a great deal in the smooth progress of my research. My research was funded through collaborative research grants of Natural Sciences and Engineering Research Council of Canada (NSERC). I would like to acknowledge FortisBC, City of Penticton and NSERC for the financial support for this research. Furthermore, I would like to take this opportunity to express my sincere thanks to municipal infrastructure managers who provided their feedback and agreed to implement the tools I developed in this research.

The support I received from the research team of the project life cycle management laboratory has been immense. I would like to express my special thanks to Ms. Hirushie Karunathilake,

Mr. Piyaruwan Perera, Dr. Gyan Kumar Chippi-Shrestha, Mr. Fasihur Rahman, Mr. James Hager, and Mr. Feng Haibo.

I would like to thank my parents who always had given their full support in all my efforts. Their love and support have made me into the person I am. I consider myself fortunate to be their son.

Last but not least, I would like to thank my wife, Kaushalya for her warm support during the past years. Without her love, support, and patience, accomplishing any of my achievements would not have been possible.

To My Family

Chapter 1 Introduction

1.1 The Challenge

One of the foremost outcomes of the United Nations Paris Agreement in 2016 was a commitment to limit the global temperature increase to 1.5°C above the pre-industrial levels (United Nations Framework Convention on Climate Change 2016). This target requires strengthening the climate change mitigation plans more than ever before in the history. Reducing greenhouse gas (GHG) emissions and reducing the environmental footprint have been priority themes of the Federal Sustainable Development Strategy of Canada from 2013-2016 (Environment Canada 2013). In order to support the ongoing climate action agenda, majority of the public sector organizations in British Columbia (BC) have signed the BC climate action charter, and have committed to become carbon neutral by 2012 (Government of British Columbia 2013b). In the quest of becoming carbon neutral, municipal governments are compelled to implement programs and policies that contribute to reducing the carbon footprint of both corporate and community actions. In fact British Columbia`s energy step code requires buildings to be net-zero ready by 2032 (Office of Housing and Construction Standards 2016). Improving the energy efficiency of buildings is one of the most viable ways to achieve institutional climate action targets, since buildings emit approximately one third of the GHG emissions in Canada (Frappé-Sénéclauze & Kniewasser 2015).

There are over 28000 federal buildings and a large number of municipal buildings operating in Canada, collectively accounting for 15% of the Canadian infrastructure portfolio (Mirza, 2007; Environment Canada, 2013). Currently, Canada's public building infrastructure is aging and has undergone considerable deterioration. Consequently, public buildings have become one of the main emitters of GHGs and smog in Canada (Zhao et al. 2012; Lin & Young 2009; Federation of Canadian Municipalities 2011). Canadian infrastructure report card reveals that based on the reinvestment levels, the condition of building infrastructure is anticipated to deteriorate in the future (Canadian Infrastructure Report Card 2016). The reports of Government of British Columbia, (2013b) and Government of British Columbia (2016) indicate that buildings account for over 75% of the corporate GHG emissions by public sector institutions. Since there is a large number of operating buildings in Canada, there is an urgent need to focus on maintenance and renovations of existing buildings to enhance their energy performance, so as to comply with the climate action targets (Industry Canada 2013; Hall 2014). A number of challenges are associated with sustainable asset management, such as increasing renewal deficits, strict environmental regulations, and budget limitations for maintenance and deterioration of aging assets (Halfawy et al. 2008).

Proactive operation and maintenance of existing buildings enhance the energy performance of a building while managing the deterioration (Min et al. 2016). Currently, there is a disconnect between the operational knowledge and decision-making process associated with municipal infrastructure management (Federation of Canadian Municipalities 2003). Timely interventions could avoid accelerated deterioration in the later stages (this is identified as the sweet spot) (Grussing 2009a). These decisions are challenged by a great deal of uncertainty due to technical advancements, fluctuations in costs, interest rates, inflation and climate change. Public sector organizations have a fiduciary responsibility to govern the tax payer money in the best possible way. Hence, a paradigm shift is needed in asset management of public buildings through integrated and hybrid approaches that focus on improving energy and GHG performance while maintaining the condition rating.

1.2 Research Gap

The premise for this research was ideated from the aforementioned challenges faced by public sector institutions in their operational management of building infrastructure. More specific knowledge gaps on the building asset management are presented below:

Lack of tools for building asset management and continuous performance monitoring: Canadian infrastructure report card[1] revealed that only 35% of small municipalities, 56% of medium size municipalities and 62% of the large municipalities have formal asset management practices (Canadian Infrastructure Report Card 2016). Through discussions with infrastructure managers, it was revealed that even those municipalities which have formal asset management practices are currently using are currently using in-house developed tools for building management, which are not comprehensive.

---

[1] Canadian Infrastructure report card survey includes responses from 120 municipalities where 56% of the Canadians reside. This is a good response rate given that the usual response rate for a survey is around 10%. Further, a similar questionnaire requires extensive resources.

Lack of research on building asset management: Published literature highlighted that lack of standardized methods for deterioration, risk prioritization, and optimization are main challenges for building asset management (Halfway et al. 2006). This research area has been overlooked in literature during the recent past. In fact, a database search in Compendex engineering village database returned only four journal articles for the key word search "building asset management" from 2006-2017.

Climate action is not integrated with asset management: Hybrid models that combined asset management and climate action planning has been overlooked in published literature. Only 19% of municipalities use climate change adaptation strategies in their asset management decision making (Canadian Infrastructure Report Card 2016).

Inability of incorporating future macro-economic changes into the decision making process: Lee et al. (2015) stated that identifying the most cost effective energy retrofits for a building is a major challenge (Lee et al. 2015a). The importance of optimizing energy, GHG emissions, and life cycle cost in building management is highlighted by several researchers (Chiang et al. 2014). However, due to the stochastic nature of the future, the optimized plan may not be the best course of action, since optimization ignores the interactions within factors. Halfway et al. (2006) reveled that despite the large number of commercially available software on municipal asset management, there is a lack of software that focus on long-term renewal planning. Moreover, uncertain, incomplete, vague, and qualitative data is another challenge associated with building asset management (Halfawy et al. 2008).

Based on the above noted concerns in life cycle management of building infrastructure, the following specific research questions emerged in this research:

i. How can the operational performance of building infrastructure be monitored using objective indices?
ii. How can the economic impact of retrofits be calculated while incorporating future macro-economic changes?
iii. How can building maintenance, repair and renewal activities be planned considering future technology changes?
iv. How can uncertain and incomplete data be incorporated into asset management decision making?

1.3 Motivation and Expected Benefits

Jiang and Tovey (2009) mentioned that the lack of building control systems disrupt the achieving of a building's energy performance targets. Pragmatic building management is crucial for reducing the social and environmental impacts of buildings (Jiang & Tovey 2010). Jiang et al.(2013) highlighted the importance of an effective management system in improving the energy performance of buildings. Systemic asset management practices and strategies would contribute to sustainable and prolonged operation of public buildings at a minimal cost. A good energy management program would contribute to the identification of malfunctioning equipment at an initial stage. and consequently would reduce significant amounts of carbon emissions (Jiang & Tovey 2010). Adequate investment in building asset management would prolong the service life, while reducing maintenance and reconstruction cost and risk of service disruption (Canadian Infrastructure Report Card 2016).

The motivation for the proposed research stems from two distinct realities related to public sector buildings in Canada. First, public sector building stock is in poor condition due to lack of maintenance. Second, in light of the ongoing climate action agenda, public sector institutions are struggling to reduce corporate GHG emissions by improving the energy efficiency of buildings. Literature review and state-of-the-practice industry analysis (e.g. energy efficiency retrofits used by public/private entities) show that so far building energy efficiency improvements projects have been conducted on an ad hoc basis without a systematic decision support system (Hall 2014). Moreover, since there are no comprehensive and scientific tools for building asset management, municipal facilities managers are compelled to manage their building stock by using tools and guidelines developed in-house. Furthermore, the present body of knowledge overlooks building maintenance planning methods that could integrate future changes into the decision based on a level of confidence.

This research aims to develop a climate-driven asset management framework to manage public buildings by developing long-term response strategies that prolong the service life and maintain a target service level, while incorporating the dynamic nature of the parameters such as efficiency of systems and costs and revised climate action targets. Since asset management plans are developed for long term it is important to incorporate future changes into the current decision making process. This research would assist capital planners and final decision makers in effective resource allocation and capital asset investment by providing best building management strategy. This research would also contribute in implementing and managing energy efficiency improvements in public buildings to ensure environmental protection, improved quality of life, economic viability, and welfare of Canadians. The developed resources would help in minimizing the disconnection of the operational knowledge in decision-making, which is a major problem in asset management (Federation of Canadian Municipalities 2003).

1.4 Research Objectives

The goal of the proposed research is to develop a life cycle thinking based asset management framework to improve the economic and environmental performance of public buildings. The proposed internal decision making framework will assist life cycle thinking based asset management, by determining the maintenance strategy that minimizes the financial risk for the institution. Such decisions would ensure prolonged service life of building assets with minimal operational and maintenance costs, energy consumption, and GHG emissions. Specific objectives of the proposed research are as follows:

1. Develop an indicator-based level of service (LOS) index for public buildings
2. Develop an uncertainty-based life cycle costing technique for building retrofits
3. Develop a multi-period maintenance planning framework for public buildings.
4. Develop an investment planning method to achieve net-zero emission in public buildings

1.5 Public Aquatic Centre Building

The above-mentioned objectives were demonstrated using a public aquatic centre building operating in Okanagan, BC. Public aquatic center buildings are one of the most highly energy consuming building types in the public building stock. In fact, the physical condition of recreational facilities are the worst compared to other classes of municipal infrastructure (Canadian Infrastructure Report Card 2016). Average annual energy consumption within a typical office building in Canada can range between 280 -350 kWh /m^2 (Natural Resources Canada 2012b), while energy consumption within a public aquatic center buildings is between 632 - 2,247 kWh/m^2 (Priyadarsini 2014). Public aquatic center buildings are comprised of more building components and systems compared to conventional buildings. These buildings are also a service center for the public. Hence, public aquatic center buildings require more systematic asset management to maintain its level of service and to prolong its life cycle. However, it has been observed that asset management of public aquatic center buildings have been largely overlooked in the relevant literature. Energy consumption within public aquatic centre buildings is quite different compared to the regular commercial and institutional buildings. Figure 1-1 shows annual energy consumption within a typical public aquatic centre buildings (Trianti-Stourna et al. 1998).

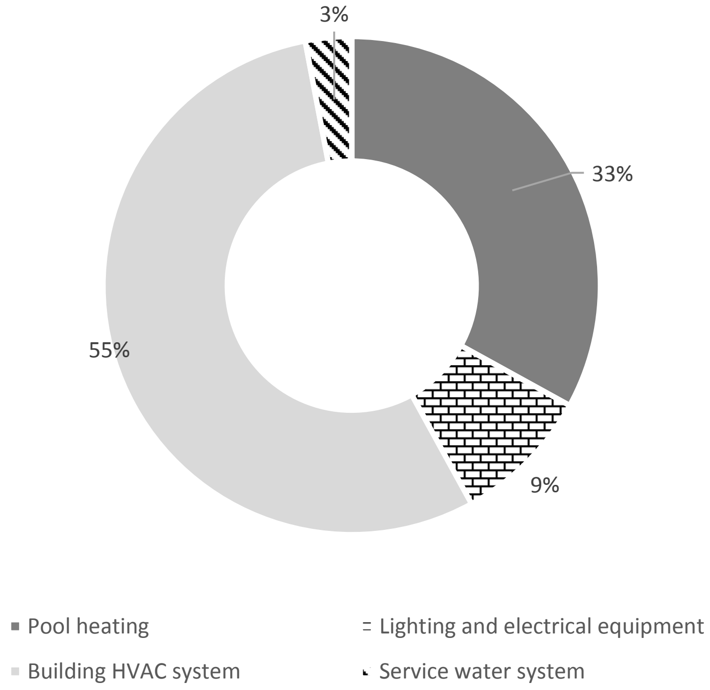


Figure 1-1: Annual energy consumption in public aquatic centre buildings

1.6 Meta Language

This section explains the specific terms used in describing the above-mentioned objectives:

Life cycle thinking: Life cycle thinking incorporates the total impacts created from a product or a process throughout its life cycle. Since this research is aimed at operating buildings, operational stage of the building is considered as the life cycle boundary. Hence, the contributions from this research are applicable to the operational stage of a building. Life cycle impacts and other stages of building life cycle (construction, demolition) were considered beyond the scope of this research.

Climate-driven operational and asset management: Climate-driven operation ensures daily operations are conducted in the climate conscious manner. Climate-driven asset management ensures the desired physical condition of building energy systems and components at the lowest life cycle cost (LCC) while achieving GHG emission reduction targets and LOS.

Public buildings: The asset management approaches proposed in this study were focused on public buildings in general. However, the case studies to demonstrate the findings were conducted for public aquatic centre buildings.

Building components: Building components and systems that mainly affect the operational energy demand were studied. Asset management interventions (i.e. maintenance, repair and replacement) are focused on reinstating the condition rating and improving the energy performance.

1.7 Thesis Organization

This thesis consists of eight chapters (Figure 1-2). Chapter 1 describes the problem statement, research gaps, motivation, objectives, methodology and overall asset management framework. Chapter 2 succinctly explains the methodology adopted in this study. Chapter 3 presents a comprehensive literature review on the related topics. Chapter 4 to 7 are focused on deliverables of this research, LOS index for public building, fuzzy based LCC technique, climate driven multi period maintenance planning approach, and NZEB investment planning method respectively. Chapter 8 discusses conclusions, contributions, limitations and recommendations. The sub objectives converge to form the life cycle asset management framework, which the overall objective. Further details of each process are discussed in following chapters.

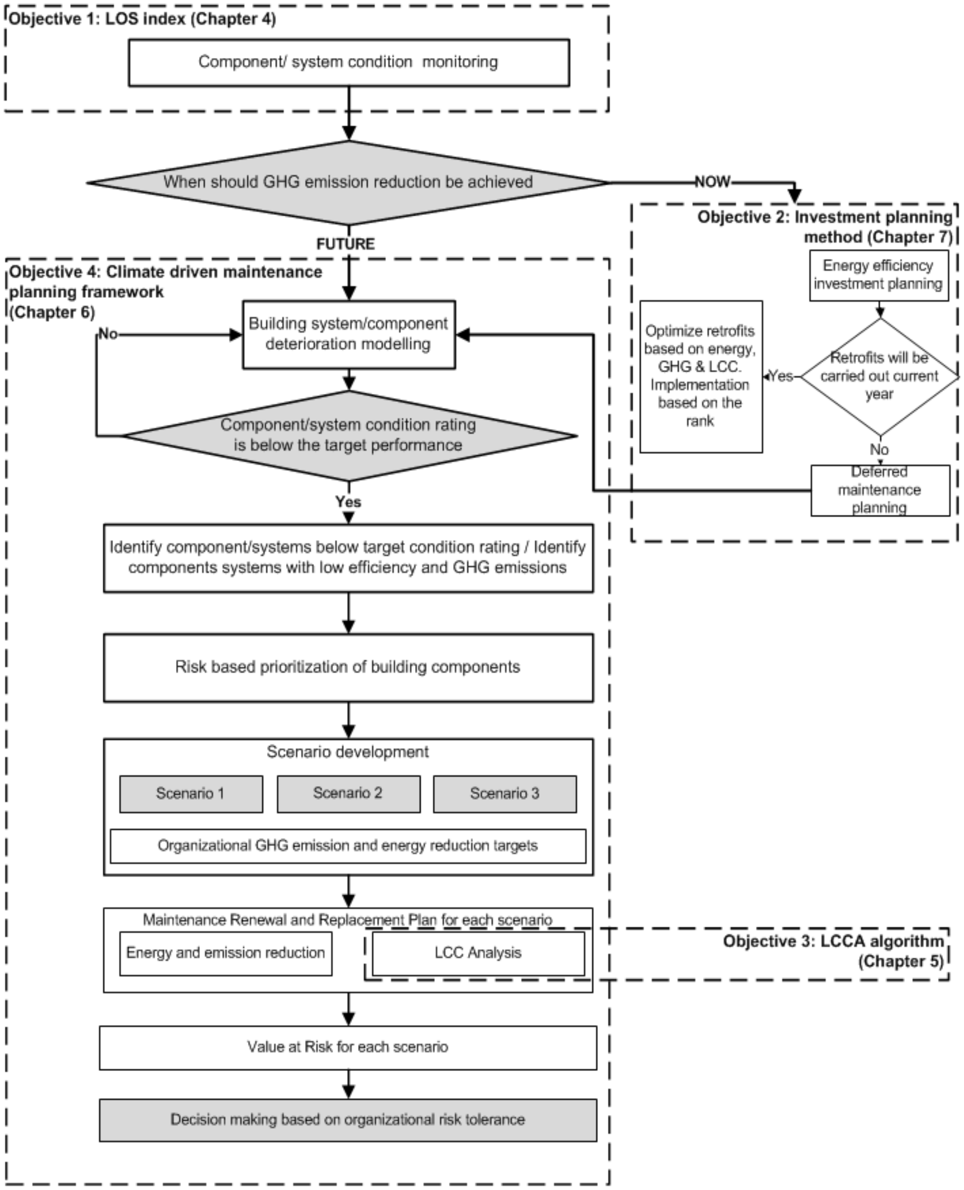


Figure 1-2: Integration of objectives and thesis organization

LOS index (Objective 1) assesses the operational performance of a public building. If the condition rating is below the target performance, requirement for interventions is triggered. NZEB investment planning method (Objective 4) sets annual budgets for retrofits which will feed into the climate-driven multi-period maintenance planning framework developed in Objective 6. This framework adopts a fuzzy based LCC technique (Objective 2) in determining the capital asset planning strategy with the least financial risk and building condition rating developed in objective 1 will be used in risk based prioritization of building components.

Chapter 2 Research Methodology

This study was conducted in multiple phases that contributed towards the development of a comprehensive asset management approach for public buildings. The overview of the methodology is illustrated in Figure 2-1. This research was carried out in six interconnected phases. Overview of the methods used in each phase in explained below. The methodology used for each objective is explained in detail in the respective chapters.

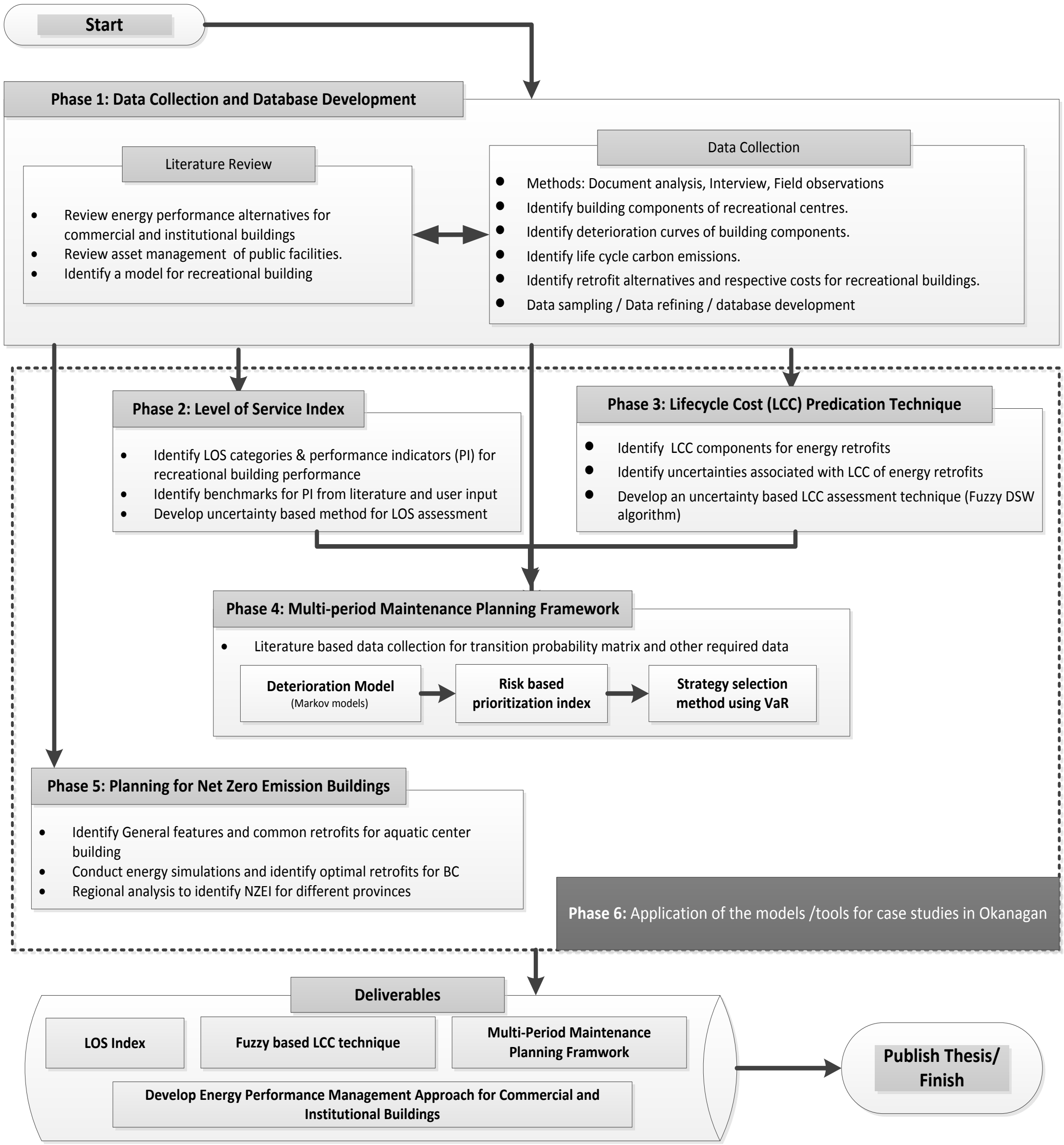


Figure 2-1: Overview of the research methodology

2.1 Data Collection (Phase 1)

An extensive literature review was conducted to collect background data. The review was based on articles published during the past 15 years in high impact factor journals on energy engineering and management. Appendix A categorizes the main research topics associated with energy efficiency enhancement of commercial and institutional buildings during the past 15 years. Multiple sources such as peer-reviewed journal and conference articles, reports published by reputed organizations, case studies, feasibility studies, cost databases, building energy codes, equipment data sheets, ISO standards, and best management guidelines were used for obtaining data for following phases. Regular communications were held with project partners for determining and refining the specific data requirements.

2.2 Level of Service (LOS) Index (Phase 2)

Informed by data collected in phase 1, an indicator-based level of service index was developed for operational management of public buildings using fuzzy logic. Summary of the methods adopted in phase 2 are as follows:

i. Operational performance indicators for buildings were identified from content analysis of sustainability rating systems (e.g. LEED, BREEM etc.), and published literature. Informed by the published literature, the aforementioned indicators were classified into LOS categories.
ii. FSE was selected as the method for synthesizing the indicators. FSE enables incorporating vague and uncertain data into decision making, and is capable of synthesizing both qualitative and quantitative data.
iii. Benchmark performance levels for indicators were identified from published data. Performance indicators specific to the institution were determined through consultations with the partner municipality.
iv. Informed by the above steps, a comprehensive index for LOS assessment was proposed.

2.3 LCCA Algorithm (Phase 3)

A fuzzy logic based life cycle cost analysis (LCCA) algorithm was developed. This method is capable of incorporating wider uncertainties. A summary of the methods used in phase 3 is as follows:

i. A fishbone diagram was developed to identify uncertainties associated with LCCA.
ii. Dong Shah Wong (DSW) algorithm was identified as the LCCA method for building energy retrofits. Probabilistic and fuzzy based LCCA methods were compared to identify DSW as the suitable method.
iii. A DSW algorithm based technique was developed for LCCA.
iv. Data for LCCA was obtained from RSMeans cost data, building energy simulations, and government websites. Green building studio software was used to simulate the impact of selected retrofits on the energy demand.
v. The fuzzy based LCCA result was compared with the deterministic result for retrofit decision making.

2.4 Climate-Driven Multi-Period Maintenance Planning Framework for Public Buildings (Phase 4)

The LCC technique developed in phase 3 and the building condition rating established in phase 2 were combined to develop the climate-driven asset management framework for multi-period maintenance planning of public buildings. This phase includes a risk based prioritization index, a multi-period maintenance planning framework and a value at risk (VaR) based decision making index. The summary of the methods used in phase 4 is as follows:

i. The literature collected in phase 1 was used to develop the climate driven maintenance planning framework.
ii. Maintenance guidelines specified by US Department of Energy and NASA were used to develop the risk based maintenance prioritization index. The condition rating proposed in phase 2 was used as the probability of failure, and a qualitative scale was used as consequences of failure.
iii. A Markov chain deterioration model was used to simulate the deterioration of building components. Conditional probabilities were obtained from literature.
iv. LCC was calculated using the LCCA technique proposed in phase 2. RSMeans database was used as a source for cost data for the analysis.
v. Fuzzy membership function of LCC was converted to a probability density function from which Monte Carlo simulation performed. The cumulative distribution function was used to determine the VaR.

2.5 Planning for Net-zero Emission Buildings (NZEB) (Phase 5)

NZEB investment planning approach was developed by optimizing energy conservation, GHG emissions, and operational cost reduction. The summary of the methods used in phase 3 is as follows:

i. A typical aquatic centre building was identified from the literature collected in phase 1 and consultations with the partner municipality. An energy model of the aquatic centre building was created using the Design Builder software. The model was validated with monitored data.
ii. The retrofits identified in phase 1 were simulated to calculate NZE investment for aquatic centre buildings. RSMeans cost data and regional tariff data were used to calculate the investment and operational costs.
iii. This study was extended to different provinces of Canada to assess the impact of different tariff regimes and grid emission factors on optimal retrofits. Weighted sum method was used to determine the optimal retrofit by considering energy demand reduction, GHG emission reduction and annualized LCC.
iv. Different combinations of retrofits were used to determine the NZE investment for the typical aquatic centre building. Furthermore, NZE investment was studied for different provinces of Canada.

2.6 Demonstration of the Proposed Methods using Case Studies (Phase 6)

These approaches were customized and demonstrated for a public aquatic centre building as case studies. An aquatic centre building owned and operated by the partner municipality was used to demonstrate the deliverables from above phases. Regular consultations were carried out with infrastructure managers and building energy management experts to ensure that the contributions of this research would serve the industry requirements.

Chapter 3 Improving the Energy Efficiency of the Existing Building Stock: A Critical Review of Commercial and Institutional Buildings

Versions of this chapter has been published in the Elsevier journals *Renewable and Sustainable Energy Reviews* and *Energy and Buildings,* as articles titled "Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings" and "Economic evaluation of building energy retrofits: A fuzzy based approach" (Ruparathna et al. 2016; Ruparathna et al. 2017).

3.1 Climate Action in Canada

Canada is committed to the Copenhagen Accord and has targeted an ambitious 17% GHG emission reduction by 2020 (612 Mt CO_2 eq[2]) and 30% by 2030 (517.6 Mt CO2 eq) from the 2005 GHG emission level (738 Mt CO2 eq) (Canada`s Action on Climate Change 2013; McDiarmid 2015). In 2012, GHG emission in Canada reached 699 Mt CO_2 eq which is 5.2 % decrease from 2005 level. GHG emissions in BC should be reduced 33% by 2020 and 80% by 2050 from 2007 levels (Ministry of Environment BC 2007). In 2012, BC reduced its GHG emissions by 4.4% from 2007 levels (Ministry of Environment BC 2012). More recent findings revealed that BC will miss achieving the aforementioned targets (Meissner 2015). More aggressive approaches are needed if Canada is to achieve the Copenhagen Accord target in 2020 (Environment Canada 2014b).

3.2 Impact of Building Infrastructure on Environment

Commercial and institutional buildings are key indicators of the socio-economic development of any nation. Despite numerous benefits to the society, significant environmental and social consequences are created throughout the life cycle of buildings (United States Environmental Protection Agency (USEPA) 2009; Industry Canada 2013). The building stock consumes approximately 40% , 25%, and 40% of the world's energy, water, and resources respectively, and is responsible for emitting one third of the total GHG emissions (United Nations Environment Programme 2015). Energy use forecasts show that in the future, the share of energy consumed by

---

[2] Mega tonnes of carbon dioxide equivalent

commercial buildings is expected to increase, while the energy consumption share of residential buildings is expected to decrease (US Department of Energy 2012a).

Statistics Canada revealed that in 2012 the total operational energy expenditure of commercial and institutional buildings exceeded CAD 24 billion, which is ~3% of the Canadian gross domestic product (Natural Resources Canada 2012a). The total energy use within commercial and institutional buildings was 1057 petajoules, which is 12% of the Canada's secondary energy use. Same buildings are responsible for emitting 11% of the total GHG emissions in Canada (Natural Resources Canada 2014b). Similar statistics are observed in other developed countries in the world. The heat discharged from the buildings in an urban settings creates the heat island effect, which is a major issue for urban centers in warm climates (Hsieh et al. 2007). Apart from the aforementioned environmental and economic consequences, buildings create intense effect on the society. As an example, Canadians spend 90% of their time within buildings, by being involved in indoor activities (Industry Canada 2013).

Poor energy performance of existing buildings is a commonly observed issue around the world (Roberts 2008). Improving the energy efficiency of operating buildings is an important step in minimizing the environmental effects of the building stock (Kneifel 2010). The basic principle of building energy efficiency is to use less energy for operations (i.e. for heating, cooling, lighting and other appliances), without impacting the health and comfort of its occupants. This approach will eventually reduce primary energy use and CO_2 emissions (Nikolaou et al. 2011; Airaksinen & Matilainen 2011). Improving the energy efficiency of operational buildings entails many environmental and economic benefits such as reduced GHG emissions and operational cost savings (Li & Colombier 2009). Hence, renovating the existing building stock is a main priority in improving the energy performance of building stock of a country (Mohareb & Kennedy 2014).

3.3 Enhancing Energy Performance of Operating Buildings

In practice, a systematic technical and management change is required to achieve greater environmental and energy targets for the future (Mohareb & Kennedy 2014). Energy efficiency and resulting cost savings are created from the interactions among the behavioral, organizational and technological changes (Figure 3-1). These elements and their interactions facilitate in achieving optimal and holistic energy performance targets (Natural Resources Canada 2014a).

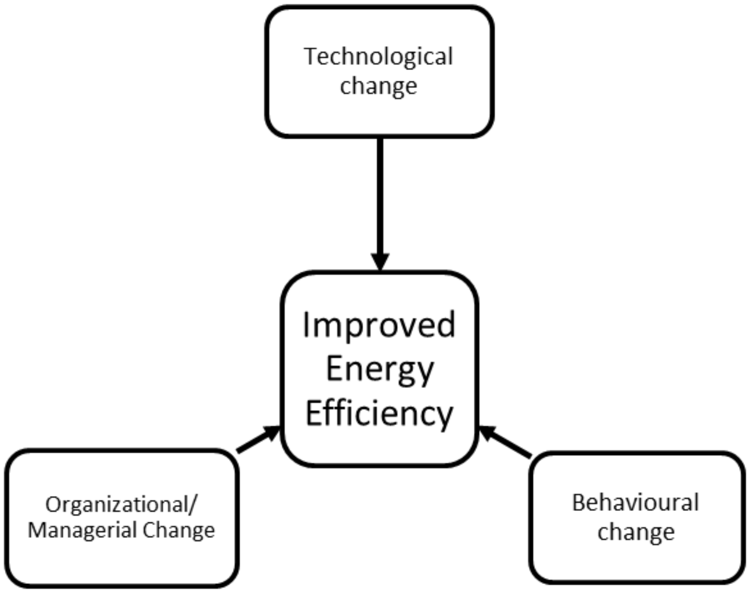


Figure 3-1: Paradigms for energy performance improvement in existing buildings (Ruparathna et al. 2016)

3.3.1 Technological changes for energy efficiency

From the mid 1990s, there has been an increase in energy efficiency patents granted for commercial and institutional buildings compared to residential buildings (Altwies & Nemet 2013). Published literature have proposed prolific methods, technologies and assemblies that reduce building energy consumption and improve the environmental performance. The above experimental approaches have a potential to achieve superior building energy performance targets in practice. Components and systems are the key determinants in the overall energy performance of a building (Pérez-Lombard et al. 2011). This section discusses approaches for improving the energy performance of main building components (i.e. building envelope, lighting system, building mechanical systems).

3.3.1.1 Building mechanical systems

Heating, ventilation, and air conditioning (HVAC) system, is the highest energy consuming component in a building (Pérez-Lombard et al. 2008). The main factors affecting the HVAC energy demand are the indoor temperature setpoint, air infiltration, window type, window-wall ratio, and internal loads (Lin & Hong 2013). In addition to that, the influence of the above parameters are dependent on building type and climate (Lin & Hong 2013). Therefore improving the efficiency of HVAC system contributes in greater energy savings within the building (Zhao et al. 2009). Studies have identified that proper selection and operation of HVAC systems can provide energy savings as much as 25% while maintaining acceptable indoor conditions (Fasiuddin & Budaiwi 2011). Literature defines two methods (i.e. passive and active measures) for reduction of HVAC energy demand (Roberts 2008). Passive measures for HVAC energy efficiency include improving the existing building conditions via means such as replacement of windows, and proper air tightness with adequate ventilation. Examples for active measures for energy demand reduction include upgrading or improving boilers and micro generation through renewable energy sources. Some of the popular active technologies for energy efficiency discussed in literature are variable frequency-driven direct expansion air-conditioning systems (Yang & Hwang 2007), variable refrgenrant flow systems (Li & Wu 2010), use of programmable thermo stats (Maheshwari et al. 2001), and inline heat pumps for water heating (Rankin et al. 2004). It is important that, these measures should not forego the thermal comfort needs of the occupants (i.e. temperature control and humidity control) and indoor air quality (Cavique & Gonçalves-Coelho 2009; Ng et al. 2013; Wang et al. 2013).

Upgrading the existing mechanical system to an energy efficient technology is a possible route to improve the energy performance of existing buildings. Several examples are discussed below. Yik et al. (2001) identified that converting from air-cooled to water-cooled air-conditioning systems enables significant electricity reductions. Bruno (2011) identified that the use of dew point evaporative could reduce the space cooling energy demand by 52-56% compared to conventional systems. According to Yu and Chan (2005) converting from head pressure control to condensing temperature control contributes in compressor power saving of 5.6%-40.2% (Yu & Chan 2005). Chua et al.(2013) identified that use of innovative dehumidification approaches and better compression methods could improve the cooling system energy efficiency by 33% and the coefficient of performance by 20% (Chua et al. 2013). A study by Fong et al. (2006) identified that optimizing the set points of water, and air supply temperatures in HVAC systems can provide monthly potential energy savings of 7% (Fong et al. 2006).

Chillers, chilled water pumps, and motors consume approximately 50% of the total energy use in commercial and institutional building (Yu & Chan 2012; Saidur et al. 2011). Hence, energy efficiency of chilled water system is important for energy performance of commercial buildings (Li et al. 2013). Energy perfromance of chillers depends on the temperature of cooling water leaving the condenser, the temperature of supply chilled water and the load factor (Yu & Chan 2012). Some researchers identified that higher capacity mechanical systems reduce the payback period of the system (Sanaye et al. 2010). However, Lee and Lee (2007) disagree with the claim that large chillers operating with higer percentage of the full capacity contribute to better energy performance (Lee & Lee 2007). Moreover, energy performance of a multiple-chiller system improves with a higher number of chillers (Lee & Lee 2007). Yu and Chan (2007) made a similar conclusion when they observed that a chiller plant with six chillers instead of four chillers pf equal size provided 10.1% electricity savings.

Utilizing natural ventilation is a viable approach to improve the energy efficiency of the HVAC system (Rupp & Ghisi 2014). Many air handling units in operation use the air economizer cycle which provides free cooling under certain exterior air conditions (Wang & Song 2013; Wang & Song 2012). Moreover, some of the studies conducted in the past have identified that night time ventilation reduces air conditioning loads in the summer (Artmann et al. 2008). However, designing and controlling a natural ventilation system for a building is a complex task due to the stochastic nature of building interior (i.e. machine loads, occupancy) and exterior (i.e. wind effect, temperature) conditions (Fontanini et al. 2013). A study by Wang and Song (2012) identified that optimal state in the air economizer cycle could be achieved through a universal control sequence with an additional airflow meter and temperature sensors (i.e. to measure supply air temperature and outside air temperature) (Wang & Song 2012).

Despite the potential energy savings, direct use of natural ventilation in a mechanically ventilation building minimizes the ability to control of indoor conditions (Chang et al. 2004). Mixed mode buildings are an innovative approach to reduce the energy consumption and GHG emissions (Center for the Built Environment (CBE) 2013). “Mixed mode” buildings use a hybrid approach to condition the building space through natural ventilation and mechanical ventilation (Ezzeldin & Rees 2013). Natural mode is used when outdoor conditions are suitable. Mechanical mode is used as a backup when outdoor conditions are not favorable (Wang & Chen 2013). Even though mixed mode ventilation suits various climates, implementation is hindered by various challenges such as lack of information, lack of understanding, and safety concerns (Center for the Built Environment (CBE) 2013).

Heat and moisture recovery is a popular approach for improving the energy efficiency of the HVAC system. Energy recovery ventilators (ERV) are used to transfer heat and moisture from exhaust air to outdoor fresh air resulting in significant energy savings (Liu et al. 2010). Past studies have identified that energy saving performance of ERV depends on outdoor climatic conditions, the enthalpy efficiency, fan power consumption, and fresh air change rate (Liu et al. 2010). Many researchers have also studied the benefits of heat recovery systems. Roberts (2008) identified that the use of a flat plate exchanger for incoming and outgoing air leads to 70% heat recovery (Roberts 2008). Another study by Wallin et al. (2012) revealed that retrofitting a traditional run-around coil heat recovery system could result in 65% heat recovery.

The shading effect in older and more established districts is a predominant factor which needs to be considered in HVAC system design. Ignoring this effect causes over design of HVAC (Cooling) system, eventually increasing the operational energy requirement (Lam 2000). However, present HVAC system designs do not consider shading effect from neighbouring buildings (Lam 2000). Lam (2000) studied the shading effect on commercial buildings in Hong Kong, and identified that 25-31% of the energy use in buildings was due to ignoring the shading effect in the HVAC design.

Even though building materials contributes to the thermal mass of buildings, the same has rarely been considered for managing the energy performance. Thermal mass elements within new and existing buildings can be exploited to achieve desirable load-leveling and peak-shifting behaviors (Talyor & Miner 2014). Thermally activated building systems (TABS) is an energy efficient and economically viable approach for building operation (Lehmann et al. 2007). TABS uses massive floors and ceilings for heat storage (Lehmann et al. 2007). Compared to mechanical methods, this method is an economic approach to improve the building energy efficiency (Talyor & Miner 2014; Lehmann et al. 2007).

There are multiple equipment operating in a building simultaneously. The general perception is that there are interactions among equipment energy consumption as well as changing climates and indoor conditions (Peng et al. 2014). However, studies showed that the reduction of lighting energy doesnot create a significant impact on HVAC energy for commercial and institutional buildings (Sezgen & Koomey 2000).

3.3.1.2 Lighting system

Lighting system consumes approximately 15% of the total building energy demand (Pérez-Lombard et al. 2008). Previous researchers have proposed numerous methods to improve the energy performance of the lighting system. These methods include installing lamps with higher luminous efficacy, task based lighting design, daylight linked lighting systems and use of occupancy sensors for work areas (Haq et al. 2014). Various factors that should be considered in selecting a feasible lighting source, including, power factor, output luminous flux, power required to operate, high current harmonic distortions, correlated color temperature, market price, and color rendering index (Khan & Abas 2011).

Converting to light emitting diode (LED) lighting system is a popular approach to improve energy performance of building lighting system (Khan & Abas 2011; Peng et al. 2014). However, Khan & Abas (2011) stressed the need for more awareness programs to spread LED lighting. Likewise, more awareness programs should be conducted to inform building managers about the alternative approaches building lighting systems and adopting appropriate technologies.

Lighting control system is another important aspect of the lighting system. Factors that should be considered in determining the lighting control system include the behaviour pattern of the occupants, geometric properties of the room or building, daylight entrance, and the work performed (Haq et al. 2014). Currently, automated lighting has been largely overlooked in retrofit projects while the same is highly popular in new building constructions (Haq et al. 2014). A large number of research studies have focused on automated the lighting systems. For instance, installing photo sensor lighting controls in day lit corridors can provide substantial energy savings (Chow et al. 2013). Moreover, the use of day light sensors for electric lighting, use of energy efficient day lighting devices, and appropriate ambient and task lighting could reduce lighting energy demand by 75-90% (Hinnells 2008). However, the unreliability of light sensor systems has been identified as a challenge in gaining market popularity (Ehrlich et al. 2002). Other challenges for automated lighting controls are the high initial cost and complicated commissioning (Haq et al. 2014). Ehrlich et al. (2002) proposed a solution that could accurately simulate photo sensor based lighting controls, which provides guidance for successful installation and operation, and reduce the need for expensive commissioning process .

Recent studies have identified that long term exposure to blue or ultra-violent lighting can cause several health concerns such as potential changes in melatonin production, disruption of human sleep cycles and risk of damage to retinal cells (Harvard Health Letter 2014; European Commission 2012; Lougheed 2014). LED lighting produces a fair amount of lighting in the blue spectrum and do not emit ultra-violet rays (Harvard Health Letter 2014; European Commission 2012). Further research is required to assess the human health risk of prolonged exposure to LED and other energy efficient lighting.

3.3.1.3 Building envelope

Improved insulation reduces the heat loss or gain from the buildings, and results in improving the thermal performance of the building (Yun et al. 2013; Peng et al. 2014; Artmann et al. 2008). In fact, a study by Chua & Chou (2010) identified that there is a strong correlation between the annual cooling energy requirement and envelope thermal transfer value. Many studies have focused on improving the energy performance of building envelope material. As an example, vacuum insulation panels enclose the building structure into an air tight envelope. Thermal performance of this technology is five times more effective than conventional insulation techniques (Roberts 2008). Gagliano et al. (2012) identified that ventilated roofs with an insulation layer results in a cooling load reduction of approximately 50%. Insulation effect can be created from as far back as the construction phase. Yun et al.(2013) identified that the use of light weight aggregate glass bubbles during the construction of the structure reduces thermal conductivity (Yun et al. 2013). However, not more than 20% glass should be used to satisfy structural properties (Yun et al. 2013).

Building fenestration geometry factors (i.e. window to wall ratio, window orientation, and room width to depth ratio) affect energy performance in all climate zones (Susorova et al. 2013). The energy savings achievable in hot climates through manipulating fenestration geometry factors is significantly high (approximately up to 14%) while it is negligible for colder and temperate climate regions (Susorova et al. 2013). Due to its importance, sundry studies have focused on improving the fenestration features to improve building energy efficiency. Several examples for innovative windows include, vacuum glazing, triple glazing and use of aero gels (Roberts 2008). Chow et al. (2011) identified that water-flow window provides significant reductions of air conditioning load and water heating loads. In fact, when compared with conventional double and single pane windows, water-flow window enables 32% and 52% heat gain reductions (Chow et al. 2011). Some of the issues associated with the above technology are energy requirement for water pumping and scarcity of water. Furthermore, replacing building transparent systems using polycarbonate enhances day lighting at a lower cost while achiving significant energy savings (i.e. by using multiwall polycarbonate panels)(Moretti et al. 2014).

Building finishes such as paint can be used to improve the energy efficiency. Roberts (2008) identified that Insulating paints based on nanotechnology enables improved thermal performance within the building. These paints possess low conduction based on the colour heat reflectivity compared to conventional paints (Roberts 2008). As an example, energy performance of buildings with high-reflectivity coating applied on the external surface is better in locations where a large temperature difference exists between daytime and nighttime (Yu Huang et al. 2013). When the difference between day time temperature and night time temperature is smaller, buildings with interior insulation perform better (Yu Huang et al. 2013).

Phase change materials can be used to increase the insulation and thermal capacity of the building envelope (Ramana et al. 2014; Borreguero et al. 2014). The use of shape-stabilized phase change materials (SSPCM) in the building envelope can exploit time-of-use utility rates by shifting the peak electrical loads to off-peak times (Zhu et al. 2011). The same authors identified that the use of SSPCM results in over 11% in electricity cost reduction and over 20% in peak load reduction (Zhu et al. 2011).

Ventilated double skin facades for buildings have been gaining popularity in the recent past. Advantages of using double skin facades include, better ventilation, reduced heat loss during wintertime, improved acoustics and improved moisture and fire safety (Manz & Frank 2005; Zhou & Chen 2010). Zogou & Stapountzis (2011) studied the effect of using photovoltaics (PV) integrated double facades in south facing walls of office buildings. The air gap between the backsides of the PV modules facilitates the use of outdoor air to cool the PV modules, which in turn increases their efficiency. The heated outflow air can be used in the HVAC system as pre-heated air, which contribute to reducing the HVAC energy requirement (Zogou & Stapountzis 2011). However, only a building with high energy efficiency can benefit by double PV façade concept (Zogou & Stapountzis 2011).

Lollini et al. (2010) observed a dynamic glazing system that can reduce energy use reductions in an office building. A dynamic glazing system can be used in windows and curtain walls and contains triple glazed system with the possibility to mechanically ventilate the inner gap. Factors that should be considered in design, construction and management of a dynamic envelope component include building typologies, (i.e. defining an open system instead of a closed one) and the ability to change the location parameters of a buildings (Lollini et al. 2010). Other innovative glazing technologies included automatic shading systems, electrocromic glazing and photochromic glazing (Roberts 2008). However, validating new technologies and implementation of new technologies are identified as the main barriers associated with building energy efficiency (Peterman et al. 2012).

Glass facade buildings have been a popular architectural consideration in the recent past. A major portion of the façade is glazed with high transmittance glazing that results in poor thermal performance (Lee et al. 2002). A large number of technologies have been adopted to improve the performance of the glazed buildings such as solar control facades, daylighting facades, active facades, double skin facades and natural ventilation. Above measures are associated with several side effects. For example, highly glazed double skin façade buildings are affected by unwanted heat gains in the summer consequently demanding a high air conditioning load (Eicker et al. 2008). Moreover, use of tinted glasses increase the lighting energy consumption of the building (Shameri et al. 2011).

3.3.1.4 Microgeneration using renewable energy sources

Numerous authors have stressed the importance of using renewable energy to improve the environmental performance of commercial buildings (Pitts 2008). Findings associated with renewable energy use within commercial and institutional buildings are discussed below.

Multifunctional renewable energy based elements are a lucrative method in achieving high performing buildings (Bansal & Goel 2000). Building integrated photovoltaic thermal (BIPVT) systems are desirable features of urban buildings that generate electricity and hot water. These features could be installed in the building as retrofits (Ibrahim et al. 2014). A study by Ibrahim et al. (2014) identified that BIPVT system improves building energy efficiency from 73% to 81%. However, the energy saving potential of this method is not yet fully utilized. Further improvements are required on energy efficiency, cost reduction and building integrated application of BIPVT features (Hussain et al. 2013). Building integrated photovoltaic panels (BPIV) windows enable significant energy savings in commercial and institutional buildings (P. K. Ng et al. 2013). In order to maximize building energy performance, it is important to customize the BIPV features according to the location characteristics (Chae et al. 2014). Existential Technology Research Center (ETRC), located in downtown Toronto, Canada has incorporated several multifunctional BPIV systems such as flexible solar membrane, solar awnings, solar louvre, and solar outdoor lab space, which produce energy while supporting the occupant behaviour (Mann et al. 2006).

Distributed generation (DG) and combined heating and power (CHP) systems are expected to play a major role in future buildings, by reducing GHG emissions and minimizing the operational cost (Ruan et al. 2009; Xu & Qu 2013; Mago & Smith 2012; Naimaster & Sleiti 2013). A study in Thailand identified that building level CHP plants would enable primary energy saving of 3.2% from 2003 levels (Gvozdenac et al. 2009). Chua et al. (2013) identified that combined cooling heating and power plants improve thermal and electrical efficiency approximately by 70%. Naimaster et al. (2013) observed that the solid oxide fuel cell CHP plants allow 7.5%-14% utility cost reductions and more than 50% of reduction in the GHG emissions. Design of DG/tri-generation systems should consider building and location parameters. As an example, solid oxide fuel cell CHP plants are well suited for colder climates (Naimaster & Sleiti 2013). Huang et al. (2011) and Huang et al.(2013) identified that tri-generation system with a bio mass gasifier would suit commercial and institutional buildings with low heat to energy ratio (approximately 0.5-0.75)(Huang et al. 2013; Huang et al. 2011).

Use of hybrid technologies at building level improves the energy and environmental performance (Haq et al. 2014; Rezaie et al. 2011). Despite its high cost, hybrid technologies are one of the best approaches for reducing the carbon footprint of buildings (Rezaie et al. 2011). Studies show that the solar thermal is one of the most cost-effective approaches for space heating (Rezaie et al. 2011). Ground-coupled heat pumps (GCHP) are a viable method for both cold and hot weather regions as a heating/cooling method for commercial and institutional buildings (Sarbu & Sebarchievici 2014; Yang et al. 2010). A hybrid GCHP systems (e.g. solar-assisted with a latent heat energy storage tank) could improve the coefficient of performance of the building heating system (Yang et al. 2010).

Building owners should consider renewable energy after having incorporated all possible energy conservation measures (Medrano et al. 2008; Yalcintas & Kaya 2009; Yamaguchi et al. 2007). A study by Yalcintas and Kaya (2009) demonstrated that energy efficiency measures are approximately 50% or more cost-effective compared to photovoltaic systems. Hence, it is important that federal and provincial policy makers opt for policies that require energy efficiency measures mandatory for any incentive payments for renewable energy sources (Yalcintas & Kaya 2009). In addition, it is important to focus beyond mere micro-generation, and identify other technical aspects associated with renewable energy technologies. As an example, installing direct current (DC) circuits for the lighting system in grid connected and PV powered buildings could reduce annual costs by 2%-21% compared to similar system with AC circuits (Thomas et al. 2012). Therefore, Authorities should establish safety regulations and standards for these innovative approaches (Thomas et al. 2012).

There are several barriers associated with micro-generation at the building level. The main barrier for micro generation in building level using renewable resources is the high upfront cost. Other barriers for micro generation include lack of reliability of the technologies, uncertainty of the fuel supply (e.g. bio fuel), and uncertain pricing structure (Wijayatunga et al. 2006).

3.3.1.5 Energy retrofitting and performance assessment

Energy retrofitting is the most preferred building GHG emission mitigation strategy (Estes 2011). Building energy retrofits are aimed at reducing GHG emissions, improving energy performance, and reducing fuel consumption while maintaining comfort levels (Picco et al. 2014) (Yu & Chow 2007). The feasibility of energy retrofits would depend on number of factors such as building characteristics and location (Kircher et al. 2010; Yu Huang et al. 2013; Liu et al. 2010). The whole building energy system should be analyzed to select feasible energy retrofits (Zhao et al. 2009). This method should be capable of detecting abnormalities in a building energy efficiency and improving performance of the building (Escrivá-Escrivá et al. 2012). Furthermore, building retrofits can be analyzed and optimized based on multiple factors such as GHG emission reduction, and life cycle cost (Vine 2003).

Building energy retrofits should reduce environmental impact (e.g., GHG emissions), gain economic benefits (e.g. improving energy performance, reducing fuel consumption), increase indoor comfort levels, and improve architectural appearance (Picco et al. 2014; Yu & Chow 2007). Effective building retrofit design requires extensive analysis of all the alternatives including linear, volumetric and material changes to the building, and exclusion of the obsolete building elements. External factors such as building orientation and location are equally important in selecting the retrofit methods (Kircher et al. 2010; Yu Huang et al. 2013; Liu et al. 2010). Most importantly, optimal decisions with regards to building retrofits should receive the acceptance of all stakeholders (Woo & Menassa 2014). Moreover, energy retrofits aim to optimize additional objectives such as environmental quality, life cycle cost, level of service, etc. Incorporating these additional objectives should be promoted through regulation, financing, and redesigning existing programs and incentives (Vine 2003).

As the first step of building energy retrofit projects, it is important to diagnose and analyze building energy consumption (Zhao et al. 2009). Thermal processes within a building are complex and difficult to understand, which makes manual calculations of building energy performance a difficult task. As a result, energy simulations are commonly used to detect abnormalities in building energy use and to assess the effectiveness of available retrofit alternatives (Roberts 2008; Escrivá-Escrivá et al. 2012). Moreover, researchers have stressed the importance of having accurate and simplified models for realistically calculating the energy performance of buildings (Melo et al. 2012; Picco et al. 2014).

There have been an increasing number of studies focused on building energy characterization. These studies provided innovative, simplified, and cost-effective methods to characterize building energy performance. Carlo and Lamberts have developed equations to classify building envelope efficiency (Carlo & Lamberts 2008). Azar and Menassa (2014) have developed a framework to quantify energy saving potential from improved operation of commercial building systems (Azar & Menassa 2014). Woo and Menassa (2014) have designed a virtual retrofit model for decision making with regards to building retrofits. This model has integrated theories and technologies such as building information modelling, building energy simulation, agent-based modeling, and multi-criteria decision making with the aid of state-of-the-art software (Woo & Menassa 2014). Menassa (2011) have developed a framework to evaluate investments for building retrofits considering uncertainties in costs and benefits, and to achieve optimal investment strategies. Moreover, several countries around the world have developed country-specific building energy performance assessment tools (Melo et al. 2012; Melo et al. 2014).

Accuracy of the energy simulation results for commercial and institutional buildings is a much-discussed topic in literature. Researchers maintain that there is usually a discrepancy between simulation data and the actual data (Roberts 2008). Bhandari et al. (2012) stressed the importance of the accuracy of energy data, especially when it is used for energy assessment and calibration. The use of less accurate data in design leads to overestimation of equipment size, which is a major setback for building performance (Lee et al. 2001). A study conducted in Hong Kong revealed that the use of realistic design data enabled 6-22% increase in building energy efficiency (Menassa 2011).

Incorporating energy-saving measures in existing buildings is a major challenge (Yamaguchi et al. 2007). Common barriers for building retrofit projects identified in literature include lack of funding, lack of interoperability, and unstructured decision-making (Woo & Menassa 2014; Mann et al. 2006; Wijayatunga et al. 2006). Moreover, despite numerous policy instruments aimed at improving building energy efficiency, the pace of innovations is deemed inadequate (Altwies & Nemet 2013). Altwies and Nemet (2013) identified the reasons pertaining to the aforementioned problem as insufficient information, disjointed decision-making, principal-agent problems, and lack of learning from dissimilar projects.

3.3.2 Building Energy Management

Many researchers have emphasized the importance of adopting organizational changes to improve the energy efficiency of buildings (Fong et al. 2006; Buck & Young 2007; Masuda & Claridge 2014; Zhao et al. 2009). The published literature reviewed revealed four important attributes associated with building energy management, which are building commissioning, energy monitoring, energy benchmarking, and standardization including energy labelling. The following sections discuss these attributes in detail.

Real-time energy monitoring is vital in improving the building energy performance (Wagner et al. 2014; Zhao et al. 2009). Energy metering is commonly used for life cycle management of the building energy performance (Masuda & Claridge 2014; Zhao et al. 2009). Energy metering helps in diagnosing issues with building energy use when there is a significant discrepancy between metered value and the anticipated value (Masuda & Claridge 2014). Futuremore, having energy sub-meters facilitates closer monitoring of secondary energy consumption (Lam & Li 2003). In order to achieve the above, researchers have emphasized the importance of effective and scientific measures to monitor the building energy use (Zhao et al. 2009). Standard design guidelines and regulations are required to guide the design and installation of energy sub-meters in commercial buildings (Lam & Li 2003).

Modern energy codes require the installation of advanced features such as daylight sensors and occupancy sensors (Tulsyan et al. 2013). A study by Kamilaris et al. (2014) revealed that real-time monitoring and behavioural changes could save up to 40% of the energy used in a building. Smart meters allow building users to see daily energy consumption patterns and encourage changes in behavioural patterns to reduce the peak demand (Roberts 2008). In fact, a study in California showed that peak demand can be reduced by 13% when customers were warned about peak energy rates. Building zone level control considering personalized occupancy patterns is another viable approach for reducing energy consumption within buildings. In fact, studies revealed that user profile based control could reduce HVAC related energy use as much as 8% in an office building (Yang & Becerik-Gerber 2014). The future of energy metering and fault detection requires smart building equipment with sensors that enable central control and remote monitoring (Hinnells 2008; Tulsyan et al. 2013).

Energy codes provide valuable guidance for managing and improving the energy performance of buildings (Radhi 2009; Yu et al. 2014). Several studies have been conducted to determine the benefits of using energy codes. For instance, Tulsyan et al. (2013) studied the energy saving potential of using energy code in India, and identified an energy saving potential through the use of the energy code ranging from 17 to 42%. Lee & Yik (2002) mentioned that if building energy code was made mandatory, annual electricity consumption in Hong Kong can be reduced by 7.9%. A study by Radhi (2009) showed that approximately 7% of electricity demand reduction could be achieved by using the energy codes in Bahrain.

Building commissioning is important, but remains a neglected area in building energy management. This approach helps to reduce energy consumption by streamlining the systems

(Bynum et al. 2012). However, benefits of commissioning fade over the years (Bynum et al. 2012). As a solution, Bynum et al. (2012) have developed a fault detection and diagnostic tool to support building commissioning (i.e. Automated Building Commissioning Analysis Tool) (Bynum et al. 2012). Similarly, Du et al.(2014) developed neural networks based tool to ensure fault detection in commercial buildings (Du et al. 2014).

Establishing building energy consumption quotas is a beneficial method in measuring the building energy consumption and use it as a basis for examining the impact of energy retrofits (Zhao et al. 2012). Energy consumption quota could be used as the threshold to assess the building energy efficiency. Furthermore, the same could be used to impose penalties for the energy users who exceed the energy quota and provide incentives for those who use energy below the quota. However, more research is required to study the effective energy standards and benchmarks for buildings.

Energy benchmarking defines a value that represents typical energy use, which will be used as the baseline against which building is compared (Chung 2012; Martin 2013). Moreover, energy benchmarking improves the energy efficiency and transparency of energy consumption, promotes competition among institutions, establishes baselines for energy labelling programs, and helps to investigate reasons for poor energy performance (Borgstein & Lamberts 2014; Chung et al. 2006; Chung 2012). Researchers have proposed numerous approaches for benchmarking building energy use. For instance, Borgstein and Lamberts (2014) proposed an energy benchmarking method considering statistical data and energy audit data (Borgstein & Lamberts 2014). Chung (2012) considered a fuzzy based linear regression model for energy benchmarking (Chung 2012). Chung et al.(2006) used energy use intensities, building age, occupants' behaviour, occupancy, maintenance procedures, indoor temperature set-point, and installations to set energy use benchmarks (Chung et al. 2006). Martin (2013) developed energy benchmarks considering energy use intensities.

Building energy labelling programs can be observed around the world (e.g. LEED, Energy Star etc.). LEED, which is the most popular building rating system, is available for currently operating buildings. LEED certified facilities enable 34% energy savings compared to conventional buildings (Sabapathy et al. 2010). Similarly, a study revealed that Hong Kong Building

Environmental Assessment Method has the potential to achieve 32% energy savings from the current levels (Lee & Yik 2002). Furthermore, other building rating systems and programs such as Energy Star (US based) , EN15251 (European Union) have also gained popularity in the past few decades (Alexandre et al. 2011). The success of an energy labelling program is critically dependent on its partnerships and alliances (Brown et al. 2002). As an example, the success of Energy Star was partially due to its partnership with federal, regional, state, and local programs. In addition to energy savings, energy labels facilitate the claiming of subsidies for energy tariffs. For instance, LEED certified buildings in India gain energy tariff subsidies (Sabapathy et al. 2010).

Despite their numerous benefits, impacts of building labeling tools have not reached the expected level. This issue is mainly because strict technical requirements stipulated by the building rating programs are not sufficient to improve the energy efficiency single-handedly (Batista et al. 2011). In addition, major building rating systems predominantly focus on building design, which makes these rating systems more suited for new buildings (Borgstein & Lamberts 2014). In order to reinforce energy efficient building practices, rating systems should focus more on performance (i.e. operation and maintenance) rather than material specifications (Andrews & Krogmann 2009).

Achieving the future energy efficiency targets require vigorous implementation of policies such as strengthening the building codes, adopting efficiency standards, labelling of office equipment and restructuring the heat metering and pricing structure (Zhou & Lin 2008; Azar & Menassa 2014). There should be best practise standards for more controlled and systematic building energy usage. Moreover, governments should support operations focused on energy management programs in commercial buildings (Azar & Menassa 2014). As an example, Canada has updated the energy code to improve the energy performance in commercial and institutional sector (Mohareb & Kennedy 2014). It is important that regulators ensure compliance to the energy codes and maintenance in the long term. Moreover, in order to ensure compliance with the national energy code for buildings, it is important to update conventional regulatory approval processes and publicize the benefits of energy efficient buildings (Yu et al. 2014). Further research is required to develop and execute policy instruments

There are several organizational barriers associated with building energy management. Studies show that buildings owned by non-profit groups are less energy efficient compared to private buildings (Buck & Young 2007). Some of the other organizational barriers affecting building energy management include volatile energy prices, meeting regulation, making a business case (i.e. difficulty in showing the monetary impact of behavioral changes), and establishing operational best practices (Peterman et al. 2012).

Importance of energy audits is an important initiative for the building energy management. A comprehensive energy audit should consider the environmental profile, occupants' behaviour, and energy devices used in the building (Kamilaris et al. 2014). Energy audits determine the energy performance assessment of the building by a credible third party. This approach is important for authorities when implementing carbon taxes. Moreover, periodic energy audits provide an objective basis for building performance assessment and rating.

3.3.3 Occupancy and operational Improvements

Many researchers have agreed that behaviour and lifestyle choices are important factors in reducing building energy demand (Hall 2014; Roberts 2008; Janda 2014; Azar & Menassa 2014; Lin & Hong 2013). Previous studies have identified that buildings which caters to a customer-base who spend considerable time on-site have a high likelihood of displaying energy inefficiencies (Buck & Young 2007). Therefore, it is important to move beyond the technical changes and explore alternative approaches such as behavioural changes to achieve superior energy performance (Janda 2014).

Improved building energy performance requires cooperation of all the stakeholders (Pitts 2008). Escrivá-Escrivá (2011) observed that even the actions of the non-specialized technical workers can significantly affect the building energy performance. An inter-disciplinary understanding of organizational culture, occupant behaviour, and technology adoption is required to set up occupancy/operation best practises (Janda 2014). Moreover, cooperative efforts are required to establish energy efficiency culture, to identify opportunities for low-carbon operations, and to execute proposed solutions by the management (Pitts 2008). The following are the seven basic actions that can contribute to reducing the energy use in buildings (Escrivá-Escrivá 2011).

i. Accurate measurement of the operational energy usage and record keeping: This action is required to identify energy over-consumption and savings.

ii. Schedule building processes and maintaining a diary: This action can contribute to the deployment of facilities according to user requirements while adhering to electricity utility contract.
iii. Automatic monitoring of electricity energy consumption: This feature enables building managers to repair or solve malfunctions in the event of an electricity consumption increase.
iv. Assign the responsibility of monitoring energy consumption to an individual: The responsibility to individual would ensure better management of building energy consumption.
v. Pro-active measures to improve the building energy efficiency: This action would support proper management of the building stock.
vi. Training building users: Provide easier understanding and control of building energy system for the building users. Intensive awareness programs would reinforce energy efficiency efforts at the organizational level (Pitts 2008).
vii. Promote communication: Promote communication between managers and users to interact and exchange information for facilitating optimal use of facilities.

Roberts (2008) identified that building occupants are more forgiving of thermal discomforts if they are provided with control to alter it. Ability of zone control and occupancy measurements enables significant energy savings while creating minimal impact on the thermal comfort (Goyal et al. 2013). Sun et al. (2010) developed a demand limiting strategy that optimizes monthly cost savings while maintaining acceptable indoor conditions through adjusting the indoor temperaure set point. This approach was able to save monthly energy costs up to 8.5%. Maheshwari et al. (2001) identified that the use of programmable thermostats in an institutional building in Kuwait enabled 25% energy savings.

Some of the researchers have stressed the difficulty in measuring the effectiveness of energy management practices and behavioral changes in commercial buildings (Azar & Menassa 2014). Furthermore, research on improving building energy performance has scarcely focused on how new approaches should be implemented in practice including socio-technical frameworks associated with them (Janda 2014). As a solution, Zhou et al.(2006) has developed a distributed energy resource choice and operations program which is capable of finding the optimal combination of installed equipment considering the utility tariffs, thermal loads and available equipment, which enables reducing the carbon emissions of the buildings (Zhou et al. 2006). Due to political challenges, gaining the support of users for occupancy reforms is an important hurdle to be surmounted (Peterman et al. 2012; Mohareb & Kennedy 2014). Other barriers associated with improving building operations include managing demand response, demonstrating success of energy efficiency programs, and improving energy performance (Peterman et al. 2012).

Table 3-1 summerizes advntages and challenges of implementing energy performance alternatives.

Table 3-1: Summary of energy efficiency improvement initiatives

Energy performance enhancement initiative		Advantages	Challenges
Technologies and assemblies	**Mechanical components**		
	Converting / Upgrading the existing HVAC system (e.g. upgrading chillers etc.)	Produce significant energy savings	Disruptive to the building occupants
			High cost of installation
	Use of natural ventilation for cooling	Provide healthy breathing air to the occupants	Use of natural ventilation depends on the outdoor conditions / season
			Difficulty to comply with energy code requirements.
	Heat and moisture recovery (e.g. energy recovery ventilators, enthalpy exchangers)	Produce significant energy savings	Performance of the system depends on outdoor conditions
	Lighting system		
	Installing state-of-the-art lighting methods (e.g. LED lighting etc.)	Low cost retrofit method	Lack of awareness with facilities managers
	Installing sensors / automated lighting controls	Reduces lighting energy demand.	Complicated commissioning
			Unreliability of light sensor systems with users High initial cost and complicated commissioning
	Building envelope and micro generation		
	Use of thermal mass elements inside the building	Shifting the peak power demand	Limited impact on the overall building energy usage
		Energy load levelling	
		Low-cost, easy to implement approach	
	Changing building fenestration geometry	Produce significant heating/ cooling energy savings	Disruptive to the building occupants
		Could reduce lighting energy demand.	High cost of construction/ installation
	Upgrading the building envelope (e.g. Ventilated double skin facades etc.)	Produce significant heating/ cooling energy savings	Complexity of validation and implementation of new technologies

Energy performance enhancement initiative		**Advantages**	**Challenges**
			Validating new technologies and implementation of new technologies
	Building level micro generation (e.g. CHP)	Significant improvements in thermal and electrical efficiency	High cost of installation
		Enhances the aesthetics of the building (e.g. building integrated photovoltaics)	Lack of reliability of the technologies and uncertainty of the fuel supply
Energy management	Energy monitoring, energy benchmarking and standardization	Help to diagnose issues with building energy use	Lack of standard design guidelines and regulations to guide the design and installation of energy sub-meters
		Facilitate in claiming subsidies and energy rebates	
	Building commissioning	Reduce energy consumption by streamlining building systems	Lack of attention provided by facilities managers.
Occupancy and operational requirements	Establish energy efficiency culture in an organization.	Involve nominal costs for organizing	Gaining the support of users for occupancy reforms is an important hurdle

Informed decision making is vital for improving the energy performance of existing buildings. These decisions are reinforced by information, incentives, knowledge and access to capital (Hinnells 2008). However, currently lack of information and know-how is a clear obstacle for energy efficiency enhancement projects (Khan & Abas 2011). The above identified barrier curtails selecting for the optimal decision with regards to building energy efficiency. In addition, lack of information hinders the building owners in pursuing potential funding sources for building energy improvements. Current approaches such as utility energy service contracts, energy savings performance contracts, and on-site renewable power purchase agreements are innovative solutions to those who lack initial funding. In addition to the funding, these approaches provide expert technical knowledge for energy efficiency enhancements.

Ruparathna et al. (2016) developed a strategy map to improve building energy efficiency. The proposed strategy map illustrates the sequence of value creation within an organization. The goal of this strategy map is to abate building energy demand and promote sustainable operation. This method shows the sequential stepwise connections between objectives to gain a superior energy performance within the building. As shown in the first level, energy performance vision of owners or the top management assists the organization to set the foundation for improved building energy performance. Secondly, the tactical management integrates the vision to the daily operations by means of best management practices (BMPs) and continuously monitors them. The tactical management should observe and respond to irregularities and publicize the success of energy efficiency improvements. As the third level, building users should alter the behavioral patterns according BMPs. This strategy would create value for the organization by fostering environmental wellbeing, economic benefits, and improved organizational image as depicted in the top levels. Figure 3-2 illustrates the strategy map for improving the building energy performance.

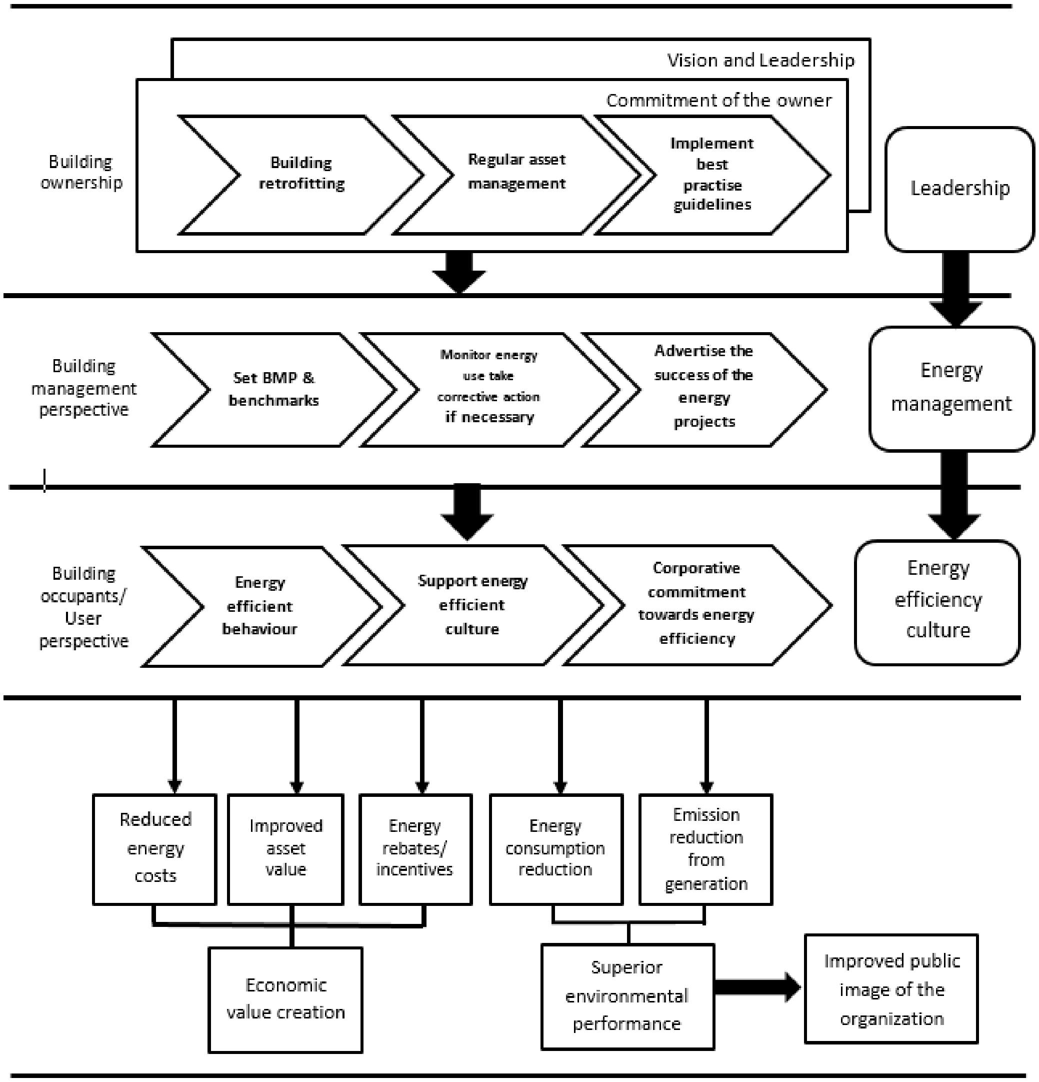


Figure 3-2: A road map for improving building energy operations (Ruparathna et al (2016)

According to the published literature, there are many approaches available for improving the energy performance of operating buildings. It is evident from the literature that that there is a considerable need for studies that are focused on behaviour-specific improvements. Hence, future studies can focus on behavior based approaches in improving the building energy performance. Further research is required to understand how organizations develop energy management best practises and implement them. Moreover, safety risks, design, installation, and regulatory barriers associated with innovative technologies should be studied before they are used in practise.

A building energy system is comprised with several components, which determines the energy performance of the building. Due to deterioration, these components would perform below their expected level. Therefore, asset management frameworks should be in place to improve the energy performance of buildings. As per the author's knowledge, there are no comprehensive studies focused on building asset management. Asset management would be a rewarding approach for improving the life cycle performance of commercial and institutional buildings.

3.4 Asset Management

Deterioration is a unavoidable process for all buildings (Richardson 2000). Chronological "Age" is one of the main factors that may contribute to the deterioration of the building energy performance (Chung et al., 2006; Sabapathy et al., 2010; Andrews and Krogmann, 2009). Multiple factors contribute in deterioration of buildings. Based on ISO 15686, Edirisinghe et al., (2015) identified seven factors in 3 categories that affect building life span (Table 3-2).

Table 3-2: Factors affecting the service life of buildings

Impact category	Factors
Quality characteristics	Design level
	Quality of construction
	Quality of component
Environment	Indoor environment
	Outdoor environment
Operating conditions	In use conditions
	Maintenance level

Building deterioration could be minimized by taking care of design stage and the selection of materials (quality characteristics) (Edirisinghe et al. 2015). Maintaining the correct operating conditions is the only route available to minimize the building deterioration during the operational stage.

The determinants for a solid facility investment strategy are lowering life cycle costs, improving the performance, and managing the risk (Grussing 2009a). Key features of an asset management system are objectivity, repeatability, and affordability (Grussing 2009b). Timely interventions could avoid accelerated deterioration in the later stages (this is identified as the sweet spot) (Grussing 2009b). As a solution to aforementioned issues, it is important to establish sound asset management practices. An effective asset management system requires assessing of the deterioration of building components, identifying effective condition monitoring methods, forecasting deterioration and resulting maintenance expenditure, decision making considering risk, cost, and sustainability throughout life cycle of assets.

Building asset management needs to consider minimizing the life cycle costs, while ensuring building performance levels related to condition, serviceability, safety, and capacity (Grussing 2013). Even though every building is unique, each building passes through similar stages in their respective life cycles. Condominium home owners association, (2012) identified five main stages in building life cycle (i.e. pre-natal stage, childhood stage, adolescence stage, adulthood, and old age). These stages are associated with various operational, maintenance, and asset renewal costs (Figure 3-3).

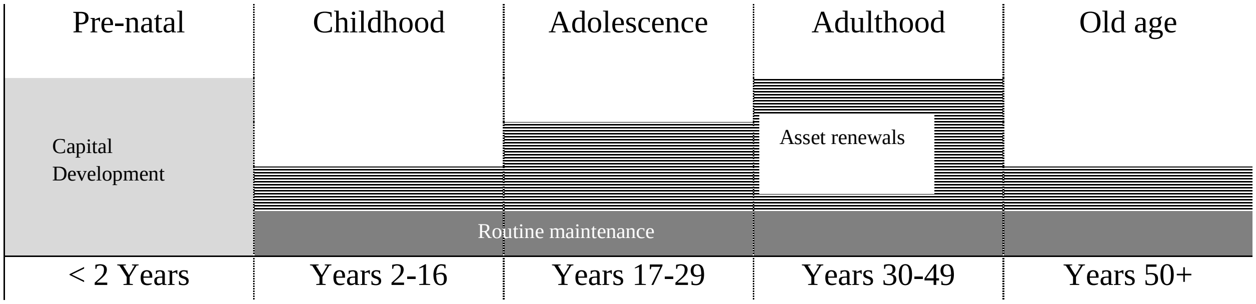


Figure 3-3: **Life cycle stages of buildings and asset management costs**

Performance of buildings and components should be measured regularly to implement interventions. Having practical and easy to use performance assessment methods are vital for assessing the performance of buildings. One of the most commonly used method in the industry for performance assessment is the use of indicator based rating systems.

Sustainable building and facilities management (FM) is a high data intensive process where data is provided by users, inspectors and sensors (Shoolestani et al. 2015). Khan et al. (2014) mentioned that rational, fact-based, reproducible, transparent, and systematic processes are required to assist this exercise. Furthermore, it has been observed that intricacy and diversity of building ownership profile affect the building performance management during the operational phase.

3.5 Building Asset Management Decision Making

Various project appraisal methods such as payback time, net present value, internal rate of return, or cost of conserved energy have been used for analyzing building maintenance to identify the best course of action (Martinaitis et al. 2007). Chiang et al. (2013) developed a framework to compute the optimal maintenance strategy for sustainable buildings considering life cycle GHG emissions, LCC, and labor requirement (Chiang et al. 2014). Wang et al. (2014) proposed a multi-objective optimization approach for building retrofit planning by optimizing energy savings and economic benefits (Wang et al. 2014a). Martinaitis et al. (2005) proposed a two factor method, which separates investments into retrofits improve energy efficiency and building renovations (Martinaitis et al. 2007). Halfawy et al. (2008) proposed a decision support system for renewal planning of sewer networks (Halfawy et al. 2008). This approach focused on optimizing the renewal costs, condition state, and risk of failure in developing the renewal plan (Halfawy et al. 2008). Kim et al. (2016) developed a model for identifying optimal green systems by thermal comfort and energy saving for educational buildings (Kim et al. 2016).

Decision making based on the capital cost can be a main drawback in infrastructure management since it ignores the operating costs of assets, which can be substantial along the life of the constructed facility (iceberg effect) (Bull 1993; Wübbenhorst 1986). Hence, during the recent past, life cycle cost became popular as a basis for making engineering related decisions. More recent literature reveals that integrated decision making approaches have been adopted in infrastructure related decision making. Innovative triple bottom line based infrastructure management decision making methods include water-energy nexus (Assaf et al. 2002; Hossaini et al. 2014); water-energy-GHG nexus (Nair et al. 2014) and eco-efficiency analysis (Seiler-Hausmann 2004; USEPA 2014).

Identifying the optimal retrofit level for buildings has been one of popular research topics in the recent years (Leal et al. 2014a; Ferrara et al. 2014). Ibn-Mohammed et al. (2013) have developed an approach to evaluate and identify economically efficient building retrofit options that achieves highest operational and embodied GHG reductions (Ibn-Mohammed et al. 2014). Ashrafian et al. (2016) proposed a framework that facilitates in identifying energy retrofits from cost and energy saving (Ashrafian et al. 2016) . Chidiac et al. (2011) proposed a regression approach to estimate the impact of building energy retrofits. Leal et al. (2014b) identified that medium efficiency is the best retrofit level from economic perspective. McArthur & Jofeh (2015) suggested an approach that identifies strategic investments for building retrofits in a building portfolio. Jafari & Valentin (2015) developed an approach that identified the optimal retrofit level for residential building based energy consumption savings. The findings of this study were based on a single case study and required additional case studies to improve the validity of the findings.

Simulation based optimization methods have been developed to identify cost-optimal energy efficiency retrofit configurations (Ferrara et al. 2014). Asadi (2012) used a TRNSYS, Genopt and MATLAB based multi-objective optimization model to select retrofit strategies (Asadi et al. 2012). Asadi et al (2014) proposed genetic algorithm and artificial neural network based model for assessing energy retrofits (Asadi et al. 2014a). Similar approach was used by Magnier et al. (2010) to optimize the design of a building (Magnier & Haghighat 2010). Wang et al (2014) proposed an optimization model for building retrofitting that maximizes energy savings and operational cost savings (Wang et al. 2014b). Ferrara et al. (2014) tried cost optimal configuration of near Net Zero energy building (Ferrara et al. 2014). Malatji et al. (2013) proposed a multi objective optimization model for building retrofits by optimizing energy savings and payback period (Malatji et al. 2013a). Shao et al. (2014) used a multi objective optimization (MOO) model and stakeholder requirement analysis based framework for decision making in selecting building energy retrofits (Shao et al. 2014). Zhivov et al (2012) proposed energy optimization method for operating army buildings (Zhivov et al. 2013).

3.5.1 Current Building asset management methods

There are various municipal infrastructure asset management software products that are commercially available. Based on a comprehensive review, Halfawy et al. (2006) stated a small number of software had limited capabilities in terms of long-term renewal planning (Halfawy et al. 2006). The majority of building maintenance planning methods are optimization-based approaches (Fan & Xia 2017a; Wang & Xia 2015a; Ye et al. 2015a). Most rating systems are focused on a specific component or system in a building. Furthermore, present methods are oblivious to technological advancements and related costs. Most retrofit analysis models do not consider integrated effects and focus on single major analysis (Lee et al. 2015b). Several building asset management methods have been proposed in literature. Table 3-3 compares the features of literature-based asset management systems. The majority of maintenance planning approaches proposed in the literature are focused on individual building components and do not focus on the building as a complete system. The objectives of the proposed approaches have not focused on prioritizing building components. In addition, a majority of maintenance planning approaches have not considered data uncertainty. More importantly, maintenance planning requires the incorporation of future technological and cost changes. However, none of the proposed approaches take the future technological changes into account. Furthermore, Grussing (2015) identified optimized building maintenance intervention planning considering energy savings as a future research area.

A study similar to the proposed research is the building façade maintenance management method proposed by Lacasse et al. (2008). This approach used Failure Mode Effect and Criticality Analysis in developing a criticality index in prioritizing façade components. Markov chain deterioration was used to model the deterioration. This method only focused on building façades. Moreover, this method does not account for future technological changes. Another study, Keshavarzrad (2015), developed an asset management approach for community buildings. This approach proposed a methodology to integrate deterioration and cost to optimize maintenance requirements. Grussing (2016) developed a probabilistic framework for characterizing building component condition degradation, which was used to identify optimal interventions during the operational stage. Zhang (2006) developed a Markov based optimization model for FM of building systems. This study focused on optimizing the management actions to allocate limited resources effectively.

Table 3-3: Comparison of building maintenance planning methods

	Focus	Life Cycle Cost	Managing energy and GHG performance	Managing the physical condition	Retrofit+ operational planning (Multi-period)	Data uncertainty	Optimized action plan	Risk based prioritization	Future changes in technology and cost	Risk based investment strategy planning
Chiang et al (2014)	Sustainable building operational management through optimizing life-cycle carbon, cost and labor.	Y	Y	N	N	N	Y	N	N	N
(Fan & Xia 2017b)	Multi-objective maintenance planning model for building envelope retrofitting.	Y	Y	N	N	N	Y	N	N	N
(Wang & Xia 2015b)	Improving energy efficiency of a building through optimization maintenance planning approach.	Y	Y	Y	Y	N	Y	N	N	N
(Ye et al. 2015b)	Optimized maintenance planning approach for energy efficient lighting retrofits	Y	Y	Y	Y	N	Y	N	N	N
(Fan & Xia 2016)	Optimized building envelope maintenance planning method to increase energy and cost savings	Y	Y	Y	Y	N	Y	N	N	N
(Lacasse et al. 2008)	Maintenance management planning for building façades	Y	N	Y	Y	N	Y	N	N	N
(Keshavarzrad 2015)	Deterioration prediction of building components	N	N	Y	N	N	N	N	N	Y
(Grussing 2015)	Sustainability focused operational management approach for existing buildings.	Y	N	Y	Y	N	N	N	N	N
Zhang (2006) (Zhang & Asce 2006)	Optimized maintenance planning for building network	Y	N	Y	N	N	Y	N	N	N
(Augenbroe et al. 2009)	Investment planning strategy for enhancing the energy performance of an existing building portfolio	Y	Y	N	Y	Y	Y	N	N	Y

Y : Yes N : No

3.5.2 Building maintenance alternatives

Building maintenance is the upkeep of components and systems of the building in proper conditions. Building maintenance alternatives can be categorized into three categories.

Corrective/ reactive maintenance: This strategy ignores preventive maintenance and operates the component until it fails. Repair or replace decision is taken following the failure. This strategy has been criticized for degradation of the reliability, frequent replacements, and the cost damages from the component failure. This strategy requires less cost and staff, and only can be justified for non-critical components whose consequences of failure are not significant or for components where no preventive maintenance is available (Schneider et al. 2006).

Preventive maintenance: Preventive maintenance ensures no failures or significant damages for caused for components/ systems. This method is estimated to achieve 12%-18% more cost savings compared to reactive maintenance. Other benefits of preventive maintenance include increased component life cycle, energy saving, and increased reliability. Disadvantages include high labor intensity, inability to prevent catastrophic failures, and execution of unneeded performance. Time based maintenance is the most widely used preventive maintenance strategy (Schneider et al. 2006). Time intervals are determined by equipment manufacturers or experience of the operators (Wang et al. 2014a). Condition based maintenance triggers maintenance when a threshold condition is reached. This approach creates moderate maintenance costs.

Predictive maintenance: This approach is measures the degradation and eliminates/ controls causal stressors before significant deterioration. Maintenance action is triggered based on the condition of the component. Advantages of predictive maintenance include decreased equipment down time and costs, increased component service life, better product quality, and energy savings. Moreover, predictive maintenance enables 8% -12% more cost savings compared to preventive maintenance. Disadvantages include increased costs for diagnostics and need for staff training. Advantages of this method are not seen by the management (US Department of Energy 2010).

Reliability centred maintenance: This approach considers both component condition and system performance (Wang et al. 2014a). This approach evaluates and ranks possible interventions. This strategy is a feasible method where combinations of conditions exist with building components/ systems (Wang et al. 2014a). Advantages of reliability centred maintenance include minimized frequency of overhauls, eliminating unnecessary overhauls, reduced probability of equipment failures and increased reliability, focus on critical components and inclusion of root cause analysis. Disadvantages of this approach include high initial costs and training. Similar to the case of predictive maintenance, the management is oblivious to the potential benefits of this method as well.

3.6 Building Performance Assessment

Although the majority of buildings do not perform as planned, performance assessment in the operational stage has been an unpopular initiative in the building industry. Various performance evaluation approaches for buildings include benchmarking, post-occupancy evaluation (POE), balanced scorecard, critical success factors, and key performance indicators (Lavy et al. 2014a). POE has been used to obtain feedback on building performance (BRE Global 2015; Leaman & Bordass 2001). Facility performance evaluation (FPE) was introduced as an upgrade to the POE, where FPE evaluates building performance based on various categories such as aesthetics, accessibility, functionality, cost-effectiveness, productivity, safety and security, as well as sustainability (Zimring 2014).

Building performance evaluation approaches observed in the literature have been used in isolation (Oyedele et al. 2012). Total building performance (TBP) is a diagnostic approach that incorporates six features, which are spatial, acoustic, visual, thermal, indoor air quality (IAQ) and building integrity (Oyedele et al. 2012; Wong & Jan 2003; Hartkopf & Loftness 1999). This approach incorporates both subjective and objective measure to evaluate the building. TBP has been used to assess the holistic performance of commercial buildings (Oyedele et al. 2012; Wong & Jan 2003) and performance related to individual mandates (e.g. acoustic) (Mahbub et al. 2010). El shenawy and Zmeureanu (2013) developed an exergy based building rating system. This index calculates and aggregates different sustainability indicators into a single unit (Exergy) (El shenawy & Zmeureanu 2013). FM is an important feature in building performance assessment. Lai & Yik (2011) have developed a method to assess the FM operations of an apartment building (Lai & Yik 2011). Zhang and Gao (2010) have proposed an optimization based FM approach for buildings (Zhang & Gao 2010). However, literature revealed that FM overlooks the physical condition assessment of buildings and systems.

A significant body of knowledge exists on sustainability assessment aspects of the built environment. There are a large number of building rating systems, indices and tools that are currently in use (El shenawy & Zmeureanu 2013). Various energy based building assessment systems are found in published literature. A large number of sustainability rating systems are geographically dispersed (Berardi 2012). Berardi (2012) identified three different building rating systems, namely cumulative energy demand systems (focus on energy consumption), life cycle assessment (LCA) systems (focus on environmental aspects), and total quality assessment (TQA) systems (Berardi 2012). The aforementioned evaluation methods used in rating systems are classified into three classes, namely calculation-based, measurement-based, and hybrid methods (S. Wang et al. 2012).

Majority of the building rating system are credit based systems, e.g. BREEM, LEED etc. (Mistry 2007). However, indicator based systems have been commonly used in the literature to assess the sustainability performance of civil infrastructure. As an example, Dasgupta & Tam (2005) proposed an indicator based multilayered screening process to compare alternatives for civil infrastructure systems (Dasgupta & Tam 2005). Namini et al. (2014) developed an indicator based system for sustainability assessment of buildings. Vučićević et al. (2013) developed an indicator based sustainability rating system for residential buildings in Serbia (Vučićević et al. 2014). This rating system primarily consisted of indicators related to building energy consumption.

Performance assessment of infrastructure should look into various perspectives such as agency view point (performance related to municipality objectives), user view (performance related to user requirements), and community view point (i.e. infrastructure performance related to community objectives) (Transportation Research Board 2013). Hence, building performance management could be improved by studying the specific needs of user groups (Huang et al. 2013). Lai and Yik (2008) studied the user perceptions on building indoor quality parameters. This study identified thermal comfort as the most important parameter (Lai & Yik 2009)

Various drawbacks of building rating systems have been highlighted in the literature. A major criticism for building rating systems is related to the length of time spend on project evaluation (Namini et al. 2014). Complexity of sustainability rating systems have been found to create hindrance while adopting in practise (Berardi 2012). Rogers in his innovation diffusion theory maintains that complexity of an innovation can affect its adaptation. It is noted that economic aspects of buildings have been ignored in many rating tools. BREEM and LEED do not consider social or economic criteria when rating a building (Berardi 2012). DGNB is the only rating system that considers economic aspect (Green Building Council Denmark n.d.). Moreover, all third party building rating systems are not comprehensive as they do not simultaneously address social, environmental and economic aspects. Despite the large body of knowledge, only limited rating systems have survived in practical use. Nguyen and Altan (2011) compared building sustainability rating systems based on multiple criteria (i.e. popularity and influence, availability, methodology, applicability, user friendliness, accuracy and verification and data collection process) (Nguyen & Altan 2011). This study has identified LEED and BREEM as rating systems with strong bases. In this study LOS is used as a building performance assessment method.

3.6.1 Level of service

Infrastructure that fails to meet LOS standards reduces quality of life for users, the ability to support economic development, and the safety of residents (Sharma, Al-Hussein, et al. 2008). The concept of LOS was initially developed for roads, and was later extended to other infrastructure classes. LOS incorporate level of operation by defining, maintenance and level of availability as an indicator of the capacity (Chasey et al. 1997). Ireland, Fearon, & Hawker, (2008) defined LOS as the performance of an asset. G.Y. Félio & Lounis, (2009) and Federation of Canadian Municipalities, (2002) identified LOS as an assessment of the quality of the service provided with respect to society and economy. Assessing the LOS assists infrastructure managers in, promoting sustainable practice, supporting decision making related to investment planning and management, and facilitating community involvement in managing the infrastructure asset (Federation of Canadian Municipalities 2002).

Determination of LOS assists the municipal decision makers in prioritizing the infrastructure assets in investment planning related to expansion, operation and maintenance, rehabilitation, and replacement of infrastructure (Ireland et al. 2008). It is important to determine performance measures and indicators needed to set and monitor the LOS (Han et al. 2015). LOS is a central part of the sustainable asset management that combines strategic asset management plan to asset condition assessment (Khan et al. 2009). Establishing LOS could differ based on the type of infrastructure asset (Federation of Canadian Municipalities 2002). LOS indicators incorporate social, environmental, and economic plans of a community and could change from one community to another (Khan et al. 2009).

Figure 3-4 illustrates parameters associated with the LOS. According to Infrastructure Canada (2002), LOS of infrastructure is assessed based on the criteria such as safety, customer satisfaction, quality, quantity, capacity, reliability, responsiveness, environmental acceptability, cost, and availability (Federation of Canadian Municipalities, 2002 ; G.Y. Félio & Lounis, 2009;Ireland et al., 2008).

Figure 3-4: LOS Parameters

Each parameter that defines LOS is explained below.

Safety: Occupant health and safety is affected by a building design and operation. Safe building should ensure healthy indoor air quality, ergonomic, electrical safety and accident prevention. In addition, the building should include measures to prevent potential natural and human-caused hazards to the building users (National Institute of Building Sciences 2015).

User satisfaction: Cao et al. (2015) identified user satisfaction as an important parameter in post occupancy evaluation of buildings. Insufficient operation and maintenance would result in service quality and user dissatisfaction (Siu et al. 2001).

Quantity: Quantity is the ability of buildings to serve the current demand for a building.

Capacity: Capacity assess the ability of a building to serve expected service demand in future.

Quality: Building FM services should be of high quality reaching expected quality of key stakeholders (Lepkova & Ūselis 2013; Ahmad et al. 2009).

Reliability: Capability to perform a service dependently and accurately (Parasuraman et al. 2016).

Responsiveness: Readiness to help users and provide speedy service (Parasuraman et al. 2016).

Environmental Acceptability: Environmental acceptability assess the environmental performance of the building.

Cost: Cost effective building should be the desire of every building manager. Cost effective building operation should include attributes such as low building operation and maintenance costs and longer life span (National Institute of Building Sciences 2012).

Availability: Agreed service time of the infrastructure asset to perform the agreed service function (Office of Government Commerce 2007).

Stakeholders of municipal infrastructure system includes the municipality (Agency), persons who are using the asset (Customer), and the community. The aforementioned stakeholders have different expectations from the municipal infrastructure system. LOS defines the terms of reference for quality of service provided from an infrastructure system (Khan et al. 2009). According to Han et al (2015) LOS include two paradigm, customer perspective and mangers perspective (Han et al. 2015). Sharma et al. (2008) suggested that user expectations, legislative requirements, performance standards, budget limitations, and delivery mechanisms should be considered when setting up a target LOS.

According to Transportation Research Board (2006), agencies target their expected service level by tracking track performance over time. The agency, managing the asset, has to pool considerations from the customer and society. According to Transportation Research Board (2006) the factors that are considered in setting up a target LOS for a road system include the following:

- Expected funding levels; Present condition, past performance trends;
- Policy goals of the organization, regional priorities, or priorities by route classification;
- Public opinion;
- Internal and external input and discussions with the construction industry;
- Life cycle cost and trade-off analyses and Marginal value of additional investment;

Chapter 4 Asset Management of Building Infrastructure: A Level of Service (LOS) Index for Operational Management

A version of this chapter has been accepted *(in press)* by *Sustainable Cities and Society*, an Elsevier journal, as an article titled "Developing a Level of Service (LOS) Index for Operational Management of Public Buildings" (Ruparathna et al. 2017a).

4.1 Background

Several researchers have highlighted the importance of focusing on the operational stage of a building due to its high environmental impact (Rincón et al. 2013). Lack of supervision of building performance during the operational stage and complexity of scoring systems are major issues associated with building performance assessment (Namini et al. 2014). Moreover, no further evaluation is carried out after the building rating is assigned. Performance management is an inherent part of asset management which determines objectives, measures progress against predefined objectives, and uses the findings to improve municipality's delivery of services to the community. Currently, there is a disconnect between the operational knowledge and the decision-making process associated with municipal infrastructure management (Federation of Canadian Municipalities 2003). Moreover, engineers' expert knowledge is focused mainly on the technical aspects, and ignores the service provided by the building (Han et al. 2015). Therefore, innovative approaches are required for performance improvement of public buildings though life cycle asset management.

Evaluating the performance of a facility is important for attaining strategic goals of the organization (Lavy et al. 2014b). In building rating systems there is a trade-off between the complexity and quality of results (Shohet 2003). A proactive building management requires accurate and current information (Grussing 2013). Hence, performance evaluation is an important step in building management (Shohet 2003).

Evaluation of LOS is a central tenant for asset management (Han et al. 2015). LOS indicates the ability of an infrastructure to support environmental, social and economic functions of a community, region or a country (Chasey et al. 1997). LOS has been used in infrastructure management of core municipal infrastructure classes (e.g. water supply systems, pavements) to ensure the service delivery. The same concept can be adopted for municipal buildings to monitor and manage building performance. Advanced asset management systems require LOS to be defined using measurable gauges that can be monitored through established performance indicators (Asset Management BC 2011). This chapter develops a LOS index for building performance management. The proposed index would enable operational performance monitoring of buildings to ensure that buildings conform to desired features and delivers desired services. Based on the above definitions, LOS for a public building infrastructure can be defined as an assessment of the operational performance provided to the building users and society. Environment-conscious performance is embraced by the contemporary world. Hence, environment consciousness is an important parameter defining the building service. Operational performance provided to users is being assessed based on the LOS parameters defined by Federation of Canadian Municipalities, (2002).

LOS occurs at multiple levels, e.g. components, assets, systems and agency wide (USEPA 2010a). The same concept could be adopted for building infrastructure as shown in Figure 4-1. As illustrated in Figure 4-1, setting the LOS for building components (e.g. window) would facilitate in achieving the LOS of building systems (e.g. building envelope). Maintaining the LOS of building systems would enable achieving LOS of the building. USEPA, (2010) defined the aforementioned as roll up LOS.

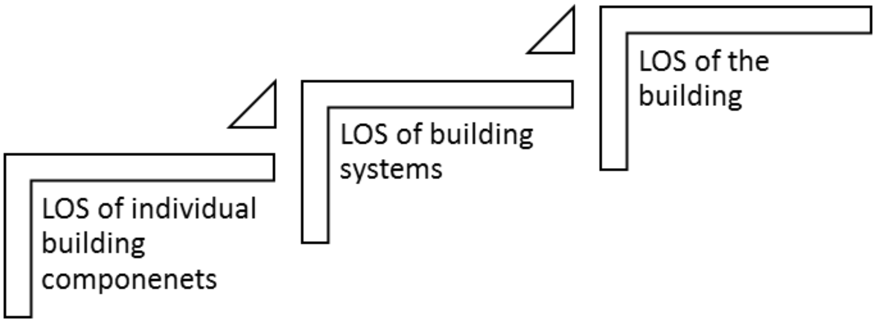


Figure 4-1: LOS propagation for buildings

LOS occurs at both asset and customer levels (USEPA 2010b) . According to USEPA, (2010b) there are internal and external LOS targets. External LOS are strategic targets that are determined by customer demand and local legislative body requirements (e.g. building level) (USEPA 2010b). Internal LOS targets are tactical, and focus on the management of operations (e.g. component, system and building level).

The literature review indicates that there is no standard method to assess the LOS of infrastructure as several methods have been used in the calculation of LOS. One of the studies viewed LOS from various users of the infrastructure asset. Sharma et al. (2008) used pedestrian LOS, bicycle LOS and vehicle LOS when assessing the overall asset LOS of municipality/urban roads (Sharma, Al-hussein, et al. 2008). Han et al. (2015) used a hierarchical framework to assess LOS related to water infrastructure focusing on TBL of sustainability (Han et al. 2015). This study has been conducted by using a customer survey. A psychometrical scaling technique was adopted by Correia and Wirasinghe (2008) to assess the LOS of airport departure lounges (Correia & Wirasinghe 2008). This approach adopted surveys where passengers were requested to rate service characteristics relative to preference, importance, and satisfaction. Above mentioned approaches are primarily survey-based, which require significant resources. However, these surveys do not look into wider parameters (defined in Figure 3-4) associated with the LOS. The use of an objective approach in the assessment of LOS would ease the present challenges in LOS assessment.

Advanced asset management methods require LOS to be defined using measurable gauges that can be monitored through established performance indicators (Asset Management BC 2011). LOS indicates the ability of an infrastructure to support environmental, social and economic functions of a community, region or a country (Chasey et al. 1997). LOS has been used in infrastructure management of core municipal infrastructure classes (e.g. water supply systems,) in ensuring the service delivery. The same concept can be adopted for municipal buildings to monitor and manage building performance. This chapter aims to develop a level of service index (LOSI) for building performance management. The proposed index would enable operational performance monitoring of buildings to ensure that buildings confirm to desired features and delivers desired services. A comprehensive LOS assessment approach was developed for buildings. This approach adopts fuzzy set theory to account for operational data and benchmark uncertainty. LOS performance indicators (PI) were identified from literature and customized for an aquatic centre building. A case study was performed to demonstrate the tool with actual data from Okanagan, BC, Canada, for different priorities. The proposed LOSI bridges the gap between the practicality and scientific rigour of a rating system. The proposed approach would assist all three layers of infrastructure management decision makers in municipalities (i.e. strategic, tactical and operational) in planning, standard setting, and operational monitoring.

4.2 Methodology

A comprehensive framework was developed to assess the LOS of buildings. This approach incorporates fuzzy synthetic evaluation (FSE) in assessing the building performance. The proposed framework includes sequential steps in assessing the LOS of building infrastructure.

4.2.1 Fuzzy Logic

Zadeh (1965) proposed fuzzy sets to deal with imprecise data and subjectivity. This is a breakthrough theory to represent vague knowledge. Fuzzy set theory helps to deal with non-statistical uncertainty. In this theory, a fuzzy set (A) is represented by an object (x) and a grade of membership to the membership function[3] x: $\mu_A(x)$. The membership value is the grade of possibility that an element x belongs to set A. The two main conditions for a fuzzy set to satisfy are normality and convexity.

4.2.2 Fuzzy Synthetic Evaluation (FSE)

Deterministic evaluation of an ill-defined object can be complex, vague, and distant from the reality. Fuzzy synthetic evaluation (FSE) is a process of evaluation where several individual elements and components are synthesised into an aggregate form. FSE can be used to handle uncertainties associated with data and information, aggregated categories, and overall index rating (Umer et al. 2016). FSE accommodates both numerical and non-numerical data in evaluation by adopting linguistic terms (Ross 2005).

Following example explains FSE in detail. LOS performance of a building is evaluated based on performance categories such as safety, quality, reliability etc. LOS performance level of a building is measured using a linguistic scale (i.e. excellent, superior, adequate, inferior). After consultation with experts, a membership could be developed that assign relations between different perspectives. $\underline{R}$ represents the fuzzy relationship between performance factors and levels.

---

[3] Membership function is different from the probability density function as latter represents the probability of a random variable within a sample space.

$$\underline{R} = \begin{array}{r} \\ Safety \\ Quality \\ Reliability \\ . \end{array} \begin{bmatrix} Excellent & Superior & Adequate & Inferior \\ 0.8 & 0.5 & 0.3 & 0 \\ 0.1 & 0.2 & 0.5 & 0.7 \\ 0.1 & 0.3 & 0.5 & 0.8 \\ . & . & . & . \end{bmatrix}$$

The LOS of a selected building is provided as membership to performance categories ($\underset{\sim}{w}$).

$$\underset{\sim}{w} = \{\underset{\sim}{w_1}, \underset{\sim}{w_2}, \underset{\sim}{w_3}, \ldots\ldots, \underset{\sim}{w_n})$$

$$\text{where } \textstyle\sum_i w_i = 1$$

Fuzzy vector ($\underset{\sim}{e}$) contains membership values for each building for performance levels.

$$\underset{\sim}{e} = \underset{\sim}{w} \circ \underset{\sim}{R} \qquad \text{Equation 4-1}$$

4.2.3 FSE Based LOS Calculation method

Building performance is defined using qualitative and quantitative performance indices. Uncertainties are inherent in the performance evaluation of infrastructure systems. Due to the fuzziness of information, performance indicators of infrastructure systems can be estimated with different levels of certainty (most likely, minimum and maximum). Benchmarks for infrastructure performance too are associated with significant uncertainties and subjectivity (e.g. LOS). Therefore FSE is used for the performance evaluation of building infrastructure. (Ruparathna et al. 2015) have used FSE for LOS assessment of recreational centre buildings. The proposed performance management index, as outlined below, involves four steps in calculating the performance of a public building (Ruparathna et al. 2015; Khatri et al. 2011).

i. Identification and classification of performance indicators.
ii. Fuzzification of the performance indicators.
iii. Aggregation of LOS indicators and LOS performance categories using FSE.
iv. Defuzzification of the aggregated categories to calculate the building performance.

Figure 4-2 illustrates the methodology adopted for assessing the LOS of buildings.

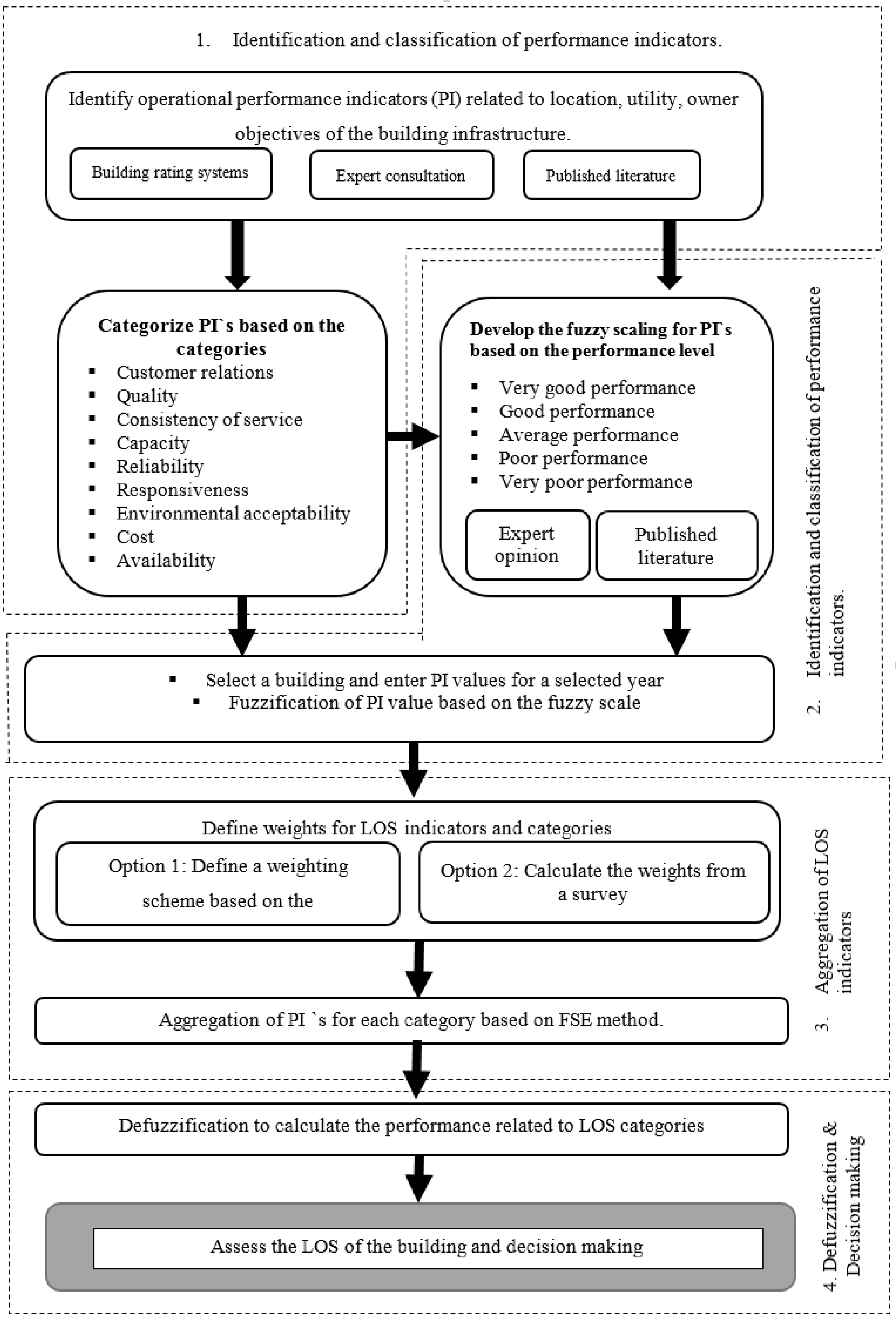


Figure 4-2: LOS assessment methodology

4.2.4 Identification and Classification of Indicators

A comprehensive review was conducted to identify building operational performance indicators (Appendix B). Indicator based systems have been commonly used in the literature to assess the sustainability performance of civil infrastructure. As an example, Dasgupta & Tam (2005) proposed an indicator based multilayered screening process to compare alternatives for civil infrastructure systems. Published literature and established building rating methods were used to identify performance indicators. Appendix B lists the sources used for identifying operational performance indicators. Identified indicators were classified into LOS categories identified in section 3.6.1 based on published literature. Table 4-1 presents the classified indicators according to the LOS categories. The indicators stated in Table 4-1 include building performance indicators (BPI), system performance indicators (SPI) and component performance indicators (CPI). Only building level indicators were focused upon in this study.

Table 4-1: Classification of indicators

Applicable to Building (B) / System (S) / Component(C)	Indicator		Safety	Quality	Quantity	Capacity	Reliability	Responsiveness	Environmental acceptability	Cost	Availability
B	I_1	Availability of measures for protection against vandalism and security	✓								
B	I_2	User satisfaction level (Through a survey)	✓	✓	✓	✓	✓	✓	✓	✓	✓
B	I_3	Indoor air quality (IAQ)	✓								
B	I_4	Thermal comfort to the users		✓					✓		
B	I_5	Building cleanliness and visual comfort to the users		✓				✓			
B / S / C	I_6	Indoor noise level		✓					✓		
B	I_7	Indoor luminance level		✓							
B	I_8	Adequacy of building amenities to users (Customizable based on the building type)		✓		✓					
B / S / C	I_9	Condition rating of building equipment				✓	✓				
B	I_{10}	Access to services in normal and emergency conditions					✓				
B	I_{11}	Number of deaths and injuries caused by using the public building (i.e. Number of safety related incidents)	✓				✓				
B / S / C	I_{12}	Non planned service interruptions as a percentage to planned service interruptions					✓	✓			
B	I_{13}	Number of user days with no service interruptions					✓	✓			
B	I_{14}	Quality of swimming pool water		✓					✓		
B / S / C	I_{15}	Annual energy use intensity (GJ/m^2)							✓	✓	
B	I_{16}	Annual renewable energy consumption (As a proportion of the total energy)							✓		
B	I_{17}	Annual GHG emission reduction							✓		
B	I_{18}	Annual water consumption per user							✓		
B	I_{19}	Amount of water recycled as a % to waste water							✓		
B / S / C	I_{20}	Average cost of operation as a percentage of annual income								✓	
B	I_{21}	Amenities for persons with disability		✓							✓
B	I_{22}	Cycling convenience for the users		✓					✓		

4.2.5 Fuzzification of the Performance Indicators

In order to establish LOS, asset managers should have predefined performance levels (Khan et al. 2014). Literature defines standard performance levels for several building performance indicators which could be used as benchmarks. Hence, both standard benchmarks and manager defined benchmarks can be established.

The method adopted by Umer et al. (2016); Khatri et al. (2011); Rajani et al. (2006) was used to develop fuzzy sets for PI based on its association to the performance benchmarks. Benchmarks defined by building owners (Appendix B) were used to generate fuzzy sets. After fuzzification each PI is expressed as a pentadruple fuzzy number. Performance level associated PIs can be in multiple forms, which are monitored crisp value (i.e. energy consumption: 6000 GJ per year), monitored uncertain value (i.e. condition rating of building components: 6-7) and qualitative value (i.e. building cleanliness and visual comfort: average). Highest membership value for performance level was selected for multiple intersections. Similar to Umer et al., (2016), pseudo numeric values were used to fuzzily and plot qualitative fuzzy numbers (Umer et al. 2016).

4.2.6 Aggregation of LOS Indicators and LOS Performance Categories Using FSE

The aggregation operation involves of combining PIs level performances to upper levels (i.e. performance category (PC) and building). The hierarchical process is presented in Figure 4-3. Pentadruple fuzzy numbers of PI were aggregated to calculate the performance related to LOS categories. LOS performance categories were aggregated to calculate the LOS of the overall building. Weighted sum method was used to aggregate PIs and PCs. Weights were defined according to the priorities of the public-sector institution.

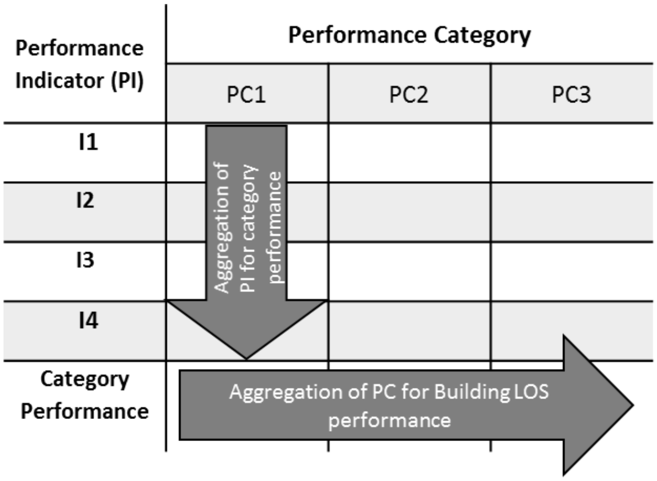


Figure 4-3: Aggregation of PI and PC to calculate LOS

4.2.7 Defuzzification of the Aggregated Indexes

Pentadruple fuzzy number derived for performance categories and the building would be made a crisp number through a defuzzification operation. A commonly used defuzzification method, the centroid method, would be used for the defuzzification operation. Overall LOS index is calculated using.

$$\boldsymbol{LOSI = D_1 C^T}$$

Equation 4-1

C^T = Transpose of a vector of centroid values of the membership functions

D = Performance of a category/building

4.3 Case Study

The proposed generic framework was customized for aquatic centre buildings owned and operated by public-sector institutions. The proposed approach was demonstrated through a case study an operating aquatic centre building in Okanagan, BC, Canada. A public-sector institution was contacted to obtain performance data for LOS. Building LOS performance levels defined by Nilashi et al., (2015) were used in the study (Table 4-2) (Nilashi et al. 2015).

Table 4-2: Performance levels for building/ categories

Performance	Very low	Low	Moderate	High	Very High
TFN	-0.2,0,0.2	0,0.2,0.4	0.3,0.5,0.7	0.6,0.8,1	0.8,1,1.2

Table 4-3 presents monitored PI values and fuzzified PI values. PI fuzzification was performed considering the benchmarks defined in Appendix C.

Table 4-3: Monitored indicator values and analysis

Indicator	Target LOS Performance	Unit	Membership Value					Monitored Performance	LOS Achieved?
			Very Low	Low	Moderate	High	Very High		
$\mathbf{I_{1}}$	Good	Qualitative	0	0	1	0	0	Moderate	No
$\mathbf{I_{2}}$	Very Good	Qualitative	0	0	0	1	0	Very Good	Yes
$\mathbf{I_{3}}$	Very Good	Qualitative	0	0	0	0.76	0.76	Good	No
$\mathbf{I_{4}}$	22-24	°C	0	0	0.34	0.66	0	23-25	No
$\mathbf{I_{5}}$	Very Good	Qualitative	0	0	0	0.76	0.76	Good	No
$\mathbf{I_{6}}$	40-45	dB	0	0	0	0	1	30	Yes
$\mathbf{I_{7}}$	500-600	lumans/m^2	0	0	0	1	1	450	Yes
$\mathbf{I_{8}}$	Very Good	Qualitative	0	0	0.66	0.32	0	Very Good	Yes
$\mathbf{I_{9}}$	Good	Qualitative	0	0	0.5	0.74	0.25	Moderate	No
$\mathbf{I_{10}}$	Good	Qualitative	0	0	0	1	0.34	Moderate	No
$\mathbf{I_{11}}$	0	Incidents	1	0	0	0	0	3	No
$\mathbf{I_{12}}$	2%	Ratio	0	0.5	0.5	0	0	2.5%	No
$\mathbf{I_{13}}$	0	Ratio	0	1	0	0	0	98%	No
$\mathbf{I_{14}}$	Good	Qualitative/ Quantitative	0	0	0	0.66	0.66	Good	Yes
$\mathbf{I_{15}}$	500	kWh/m^2	0	0	0	0	1	426	Yes
$\mathbf{I_{16}}$	10	Percentage	0	0	0	1	0	5	Yes
$\mathbf{I_{17}}$	0%	Percentage	0	0	0	0.28	0	2%	No
$\mathbf{I_{18}}$	100	m^2/ user/year	0	0	1	0	0	90	Yes
$\mathbf{I_{19}}$	40%	Percentage	0	0	0	0.5	0	30%	No
$\mathbf{I_{20}}$	Good	Cost/Income	0	0.5	0.5	0	0	Good	Yes
$\mathbf{I_{21}}$	Moderate	Qualitative	0	0	0	1	0	Moderate	Yes
$\mathbf{I_{22}}$	Good	Qualitative	0	0	0	1	0	Moderate	No

According to Table 4-3, the building did not achieve the target LOS related to 12 of the LOS indicators. Fuzzy memberships of LOS categories are presented in Table 4-4. All LOS categories have the highest membership in high performance.

Table 4-4: Memberships to LOS categories

LOS Category	Very Low	Low	Moderate	High	Very High	Highest membership
Safety	0.25	0.00	0.25	0.44	0.19	High
Quality	0.00	0.00	0.11	0.71	0.38	High
Quantity	0.00	0.00	0.33	0.66	0.00	High
Capacity	0.00	0.00	0.39	0.69	0.08	High
Reliability	0.17	0.25	0.17	0.46	0.10	High
Responsiveness	0.00	0.38	0.13	0.44	0.19	High
Environmental acceptability	0.00	0.00	0.13	0.51	0.27	High
Cost	0.00	0.25	0.25	0.50	0.00	High
Availability	0.00	0.00	0.00	0.67	0.33	High

Figure 4-4 illustrates performance related to LOS categories after defuzzification. LOS performance related to category performance is highest related to quality of service. Performance related to other LOS categories are in following order; availability, capacity, environmental acceptability, quantity, responsiveness, safety, reliability, and cost.

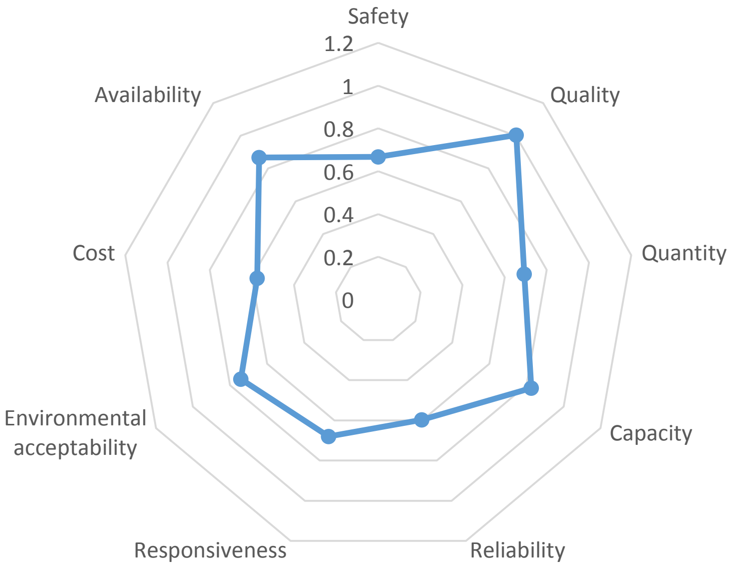


Figure 4-4: Performance related LOS categories

4.3.1 Weight schemes for overall building performance assessment

Priorities of municipalities differ from one municipality to another. Hence, universal weights cannot be defined for PIs and PCs. Weight schemes have been used by previous researchers to mitigate uncertainty of user priorities (Umer et al. 2016). This analysis adopted three weight schemes. Weight schemes and performance benchmarks were established with the consultation of the municipality and literature.

User defined: Consultations with infrastructure and planning group of the municipality were conducted to determine performance benchmarks and PC weights. Equal weights were assigned to PCs.

Pro-Environment: In this pseudo scenario, environmental performance has been given prominence. Environmental performance category was assigned higher weight. Equal weights were assigned to other PCs.

Service oriented: In this pseudo scenario, the service provided by the facility is given prominence. Equal weights were assigned to service related performance categories. Environmental performance and cost were assigned lower weights.

Memberships of overall building performance for three scenarios are presented in Table 4-5.

Table 4-5: Membership of overall building performance

LOS Category	Very Low	Low	Moderate	High	Very High	Highest membership
User defined:	0.05	0.10	0.19	0.56	0.17	High
Service oriented	0.06	0.13	0.25	0.72	0.21	High
Pro-Environment	0.04	0.09	0.19	0.56	0.18	High

Overall building performance is presented in Table 4-6. According to the analysis, the overall building performance is high and does not change based on the user priorities.

Table 4-6: Building LOS for different scenarios

Scenario	Pro-Environment	Service oriented	User defined
Building performance	0.74	0.95	0.74

4.4 Discussion

Operational performance assessment of buildings has received ample attention during the recent past. Despite providing a snap shot view, commonly used performance rating systems do not provide adequate information on managing the operational performance of buildings. LOS is commonly adopted by infrastructure managers in managing the service provided to the public. Hence, LOS could be adopted to sustain the service provided by public buildings.

LOS index proposed in this chapter has incorporated the multidimensional nature of operational indicators on LOS of buildings, which addresses a shortcoming of the previous work. The LOS assessment methodology uses FSE, which enables the use of incomplete, qualitative and vague data in the analysis. LOS assessment approach was demonstrated using a case study for an aquatic centre building operating in Okanagan, BC. Furthermore, in order to demonstrate this method, various weight scenarios were analyzed to illustrate the how the priorities of the municipality affect the LOS of the building. The LOS assessment methodology was customized to assess the LOS of the selected public aquatic centre building. The overall LOS of the building had the highest membership to high performance in all three weight schemes. Performance related to LOS categories had the highest membership to high category. However, the building did not achieve the target performance in 12 LOS indicators. Hence, building operators should more focus on the performance related to individual performance indicators. The three levels of above information would provide detailed information in managing the operational performance of the building in focus.

Building LOS approach combines asset management, build operational rating and FM. Hence, the LOS based approach incorporates a holistic view on the operational performance of a building. This research provides a unique assessment of the performance of a building asset by focusing on the condition rating of component level and system level to define the overall condition rating of the building. This scrutinized information assists asset management and resource allocation decision making by comparing the physical condition rating related to building, components, and systems. Component level and system level condition rating will identify poorly performing building components and systems, assisting building managers in implementing maintenance, repair, and renovation of buildings. Building level LOS indicates the service provided to the building users. This approach identifies underperforming LOS categories where the service could be improved through allocating more resources, by improving processes, and by retrofitting. The initiatives that could improve the LOS include energy retrofitting, improving the safety/security arrangements, and improving FM services. The cost implications could be weighed against target LOS to identify optimal LOS that could be delivered at the available budget.

The proposed approach is a self-assessment method for a public aquatic centre building. However, LOS could be used as an internal building performance management strategy by conducting intra-benchmarking among building operated by the public institution. LOS evaluation informs building users about the status of building service performance. More importantly, this information ensures the transparency of municipality operations since the facility is operated by tax dollars/ subscriptions. The proposed rating system can be implemented by the infrastructure department of the municipality. This approach could be a common basis to compare operational performance of municipal building categories. Presently, LOS is assessed for key municipal infrastructure classes. Hence, the proposed method would add to the existing system. This approach would enable annual performance monitoring of the building. The proposed approach analyses building performance related to two hierarchical levels (i.e. overall performance and categorical performance). Corrective actions could be initiated if the performance of the building is below the pre-established targets. The corrective action triggers could be related to the overall performance and categorical performance. Using the LOS enables comparing the LOS of a building with other buildings and other classes of infrastructure. Besides being an internal performance management approach, LOS could be used for continuous reporting regarding the services provided to users. Reported LOS would inform building users in comparing and selecting recreational facilities such as aquatic centres.

The municipality should define the benchmarks for the LOS based on organizational priorities. The overall LOS rating of a building is influenced by both pre-established performance benchmarks and category weights. This is one of the unique features of the proposed approach. Furthermore, LOS targets are established for several performance categories. As a responsible organization, the municipality should establish constructive performance benchmarks.

Benchmarks could further be adopted to improve the service provided by the building. Benchmarks and category weights could be used to define the priorities of the building owners.

Building LOS is evaluated by performance related to indicators through monitored performance, annual user survey, and the expert judgement of the building manager. Even though building level indicators are commonly available, obtaining performance related to component and system level indicators can be a challenge. As an example, component and system LOS assessment requires energy use information for the specific component/system. Since energy sub-metering has not been fully incorporated into building management, obtaining specific energy demand data could be a challenge. Component/ system condition is proportional to the energy consumption. Hence, assumptions can be made for component / system energy efficiency using mathematical models. Furthermore, this process requires extensive data for all stakeholders. Shoolestani et al (2015) proposed an approach that allows occupants to interact with buildings and provide feedback on buildings using building information modelling (BIM) (e.g. SocioBIM (Shoolestani et al. 2015). The proposed system could be integrated with a real-time data capturing approach that enables real time LOS assessment of the building. User satisfaction depends on number of incidents encountered. Though this could be a future technology, real time monitoring of LOS could enable the delivery of the best service to building users.

4.4.1 LOS for Building Asset Management

Roll-up LOS illustrates how the condition of components and systems will affect the overall building condition rating. As presented in Figure 4-5, condition rating of a building depends on the system and component condition rating. Condition rating of a component depends on component performance indicators (CPI), including physical condition of the component, energy efficiency, noise level etc. Condition rating of the system components and system performance indicators (SPI) defines the condition of the system (e.g. HVAC system, building envelope). Condition ratings of systems and building performance indicators (BPI) define the condition rating of the overall building.

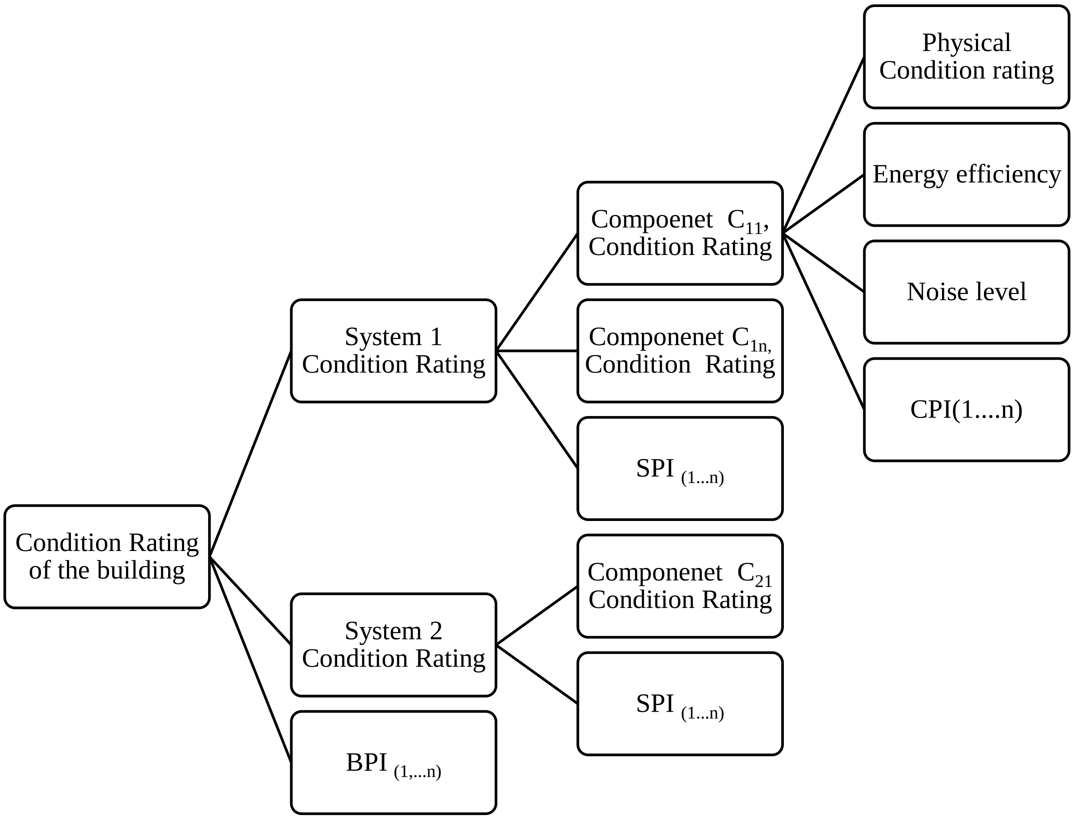


Figure 4-5: Defining condition rating of the building

Strategic, tactical, and operational management of municipalities could use this information to enhance their asset management practices. As an example, strategic management will define the vision for the institution (e.g. eco-centric), tactical management will define the operational LOS targets and performance benchmarks, and operational management will monitor the building performance and report the performance gaps to higher management. This task would be further informed by the public opinion. Furthermore, performance gaps and resource demands will redefine the LOS targets of the building (Figure 4-6).

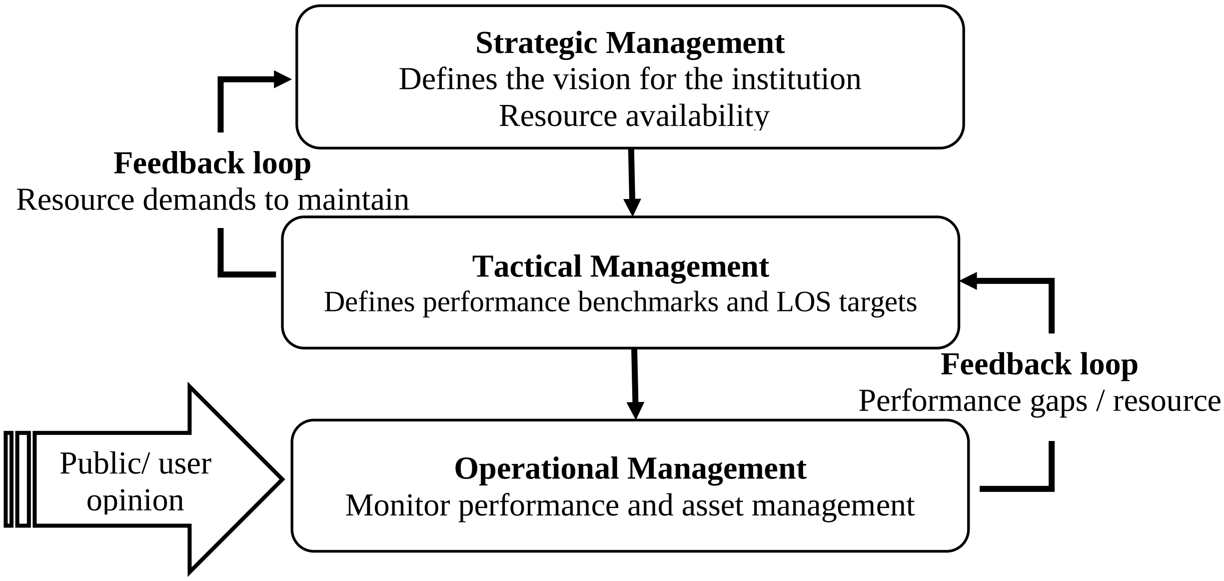


Figure 4-6: Building asset management by a public-sector institution

4.5 Summary

This chapter introduced a LOS assessment approach for building infrastructure and developed a LOS index for public recreational centre buildings. The LOS index is an objective method for assessing performance which addresses a number of shortcomings in current building performance evaluation methods. Additionally, the use of FSE enables incorporating vague, incomplete and qualitative data into the analysis. This approach would assist facilities managers in monitoring and managing the operational performance of public buildings. The proposed methodology can be customized to suit the function of the public building. Implementation of the LOS index was demonstrated for a public aquatic centre building operating Okanagan, BC, Canada. LOS index provides three levels of detail for operational management of public buildings; overall building performance for strategic management, performance of LOS categories for tactical management, and indicator performance for operational management.

Chapter 5 Economic Evaluation of Building Energy Retrofits

Version of this chapter has been published in *Energy and Buildings*, an Elsevier journal, as an article titled "Economic evaluation of building energy retrofits: A fuzzy based approach" (Ruparathna et al. 2017b).

5.1 Background

LCCA can be used to compare alternatives for building performance improvements, in order to maximize savings (Fuller 2010). There is a growing body of knowledge on LCC for built environment and civil infrastructure. Jafari and Valentin (2015) proposed a model for evaluating energy retrofits based on energy saving potential and required investment (Jafari & Valentin 2015). Menassa (2011) proposed an uncertainty based framework to evaluate sustainable retrofits (Menassa 2011). Li and Guo (2012) developed a life cycle cost prediction method for university buildings combining simple linear regression, multiple regression, and back propagation artificial neural networks (BPN) (Li & Guo 2012). Results of this research showed that BPN are able to provide the best estimation (Li & Guo 2012). Tsai et al. (2014) proposed an activity based costing decision approach for life cycle cost assessment of green construction projects (Tsai et al. 2014). This approach is expected to assist construction managers in accurately determining the energy saving potential and cost of resources of green building initiatives. Morrissey and Horne (2011) compared life cycle cost implications and environmental savings for various housing designs (Morrissey & Horne 2011). Li and Guo (2012) developed a life cycle costing method using back propagation artificial neural networks for repair and maintenance of university buildings (Li & Guo 2012). Kuusk et al. (2014) assessed the economic impacts of deep energy retrofits for Estonian multifamily residential buildings (Kuusk et al. 2014). This study identified that insulating external walls has the highest effect on reducing energy demand. Mahlia et al. (2011) analyzed LCC of lighting retrofits for the University of Malaya buildings, and found that energy savings of approximately 40% can be achieved by replacing university lighting with a T5 system (Mahlia et al. 2011).

The two main components of LCC are cost of ownership (i.e. initial costs, depreciation, insurance, taxes, storage, and investment costs) and operating costs (i.e. energy costs, maintenance costs, and repair, refurbishment, and renovation costs) (Gransberg 2015).

Moreover, end-of-life costs would be borne by the owner (i.e. environmental costs, landfill cost, and scrap value). The aforementioned costs are affected by the value and timing of future costs, service life capital recovery factor, and interest rates (Zeynalian et al. 2013; Rahman & Vanier 2004). Figure 5-1 outlines the major costs related to building energy retrofits.

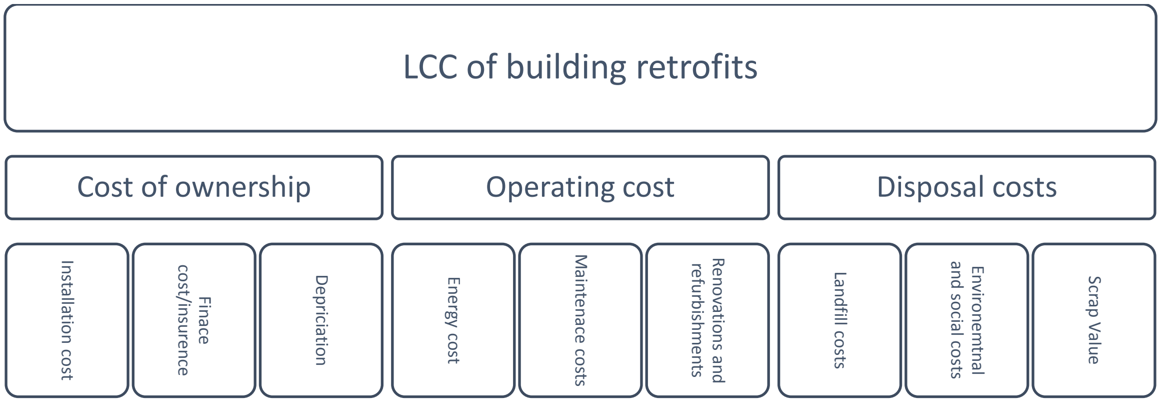


Figure 5-1: Overview of building retrofit LCC

The foundation for LCCA is time value of money (Ammar et al. 2013; Rahman & Vanier 2004). Commonly used economic evaluation methods are explained below (Fuller 2010).

- Net Savings (NS): NS is the difference between income generated from operational savings and capital investment costs. Net savings should be greater than zero.
- Savings-to-Investment Ratio (SIR): SIR is the ratio of present value of operational cost savings to capital investment costs. In order to be feasible, SIR should be larger than 1.
- Equivalent annual cost (EAC): EAC is the cost of owning the asset over time. EAC is calculated by dividing net present value by an annual equivalence factor.
- Internal rate of return (IRR): IRR is the discount rate at which the estimated NPV is equal to zero. Adjusted IRR is the annual yield from an investment when the interim returns are taken into account. IRR should exceed the expected rate of return.
- Adjusted Internal Rate of Return (AIRR): AIRR is the annual yield from an alternative over the analysis period, considering reinvestment of interim revenues at the discount rate.
- Payback Period (PP): PP is the time taken to recover the initial investment. Simple PP ignores the time value of money. Discounted PP is calculated by considering the time

value of money. Payback period should be used as a screening method and should be less than the study period.

5.1.1 Uncertainties in life cycle cost analysis

Even though conducting LCCA increases the probability of selecting projects with the best economic performance, the final LCC result is subject to significant uncertainty. Previous studies have emphasized the importance of taking into account LCCA uncertainties (Morrissey & Horne 2011). LCCA is performed during the early stages of the planning phase, where cost estimates are available rather than exact dollar amounts. Due to the volatile macro-environment, significant uncertainties are associated with LCCA variables (Dhillon 2010). Uncertainty in inputs means monitored (real) outcomes can vary from the estimated outcome (Fuller 2010). Common uncertainties associated with LCCA are as follows (International Organization for Standardization 2007).

- Errors in judgement: over-optimistic estimates, unattainable service lives, impractical maintenance programs.
- Future activities: Uncertainty in achieving the required maintenance, variations in future requirements, and potential changes in user behaviour.
- Other factors: Changes in predicted inflation rates, material and labor costs, changes in legislation, and impacts of climatic change.
- Refurbishments require a revised service life of a component.

Uncertainties associated with specific variables used in LCCA are as follows:

Energy consumption: A high level of uncertainty is associated with energy consumption since it is often difficult to predict. Other uncertainties such as user behaviour and occupancy patterns also have an impact on energy consumption of a building (Fuller 2010).

Energy prices: Energy prices are subject to various uncertainties in terms of utility rate type, summer and winter rates, rate structure, and demand charges (Fuller 2010).

Operation, Maintenance, and Repair Costs (OM & R): OM&R costs are difficult to estimate due to variations in maintenance schedules from building to building (Fuller 2010).

Uncertainties associated with prediction of service life make it a challenge to forecast the best timing of MR&R activities (Rahman & Vanier 2004).

Replacement Costs: Replacement costs depend on the frequency of replacements during the service life, and the cost of each replacement. The number of replacements required depends on the estimated useful life of the system considered and the study period (Fuller 2010).

Residual value: Residual value is calculated using resale value, value in place, salvage value, conversion costs, net of any selling, and disposal costs. This value can be calculated through proper prorating of the initial costs (Fuller 2010).

Service life and Remaining life: Forecasting the service life of infrastructure assets and their components is a major step in LCCA (Rahman & Vanier 2004). Remaining service life depends on multiple factors such as maintenance, construction, and environmental factors.

Periodic Charges: These charges include loan interest payments, contract payments for Utility Energy Services Contract (UESC), or Energy Savings Performance Contract (ESPC). These payments depend on the interest rates and other conditions of the contract.

Discount Rate: The discount rate is the investor's minimum acceptable rate of return. Generally, the discount rate is assumed to be constant over the period of analysis (Rahman & Vanier 2004).

Inflation: The general approach used in LCCA ignores real effects of inflation and assumes that all costs increase at the same rate. This assumption is erroneous, since in reality labour, material, energy, and equipment costs do not change at the same rate (Rahman & Vanier 2004).

Depreciation: There are different types of depreciation associated with engineering equipment, such as monetary depreciation, physical depreciation, technological depreciation, and functional depreciation (Dhillon 2010). Commonly used monetary depreciation methods include the sum-of-years (SYD) method, the straight line method, and the declining balance method.

The above factors have been plotted in a fishbone diagram for clarity in Figure 5-2. The fishbone diagram (Ishikawa's diagram) is used to present uncertainties related to LCCA. Dr.

Kaoru Ishikawa developed the fishbone diagram as a systematic method to visualize cause-and-effect relationships. This approach assists stakeholders in analyzing a problem and generating ideas about the causes of that issue (Coghlan & Brydon-Miller 2014).

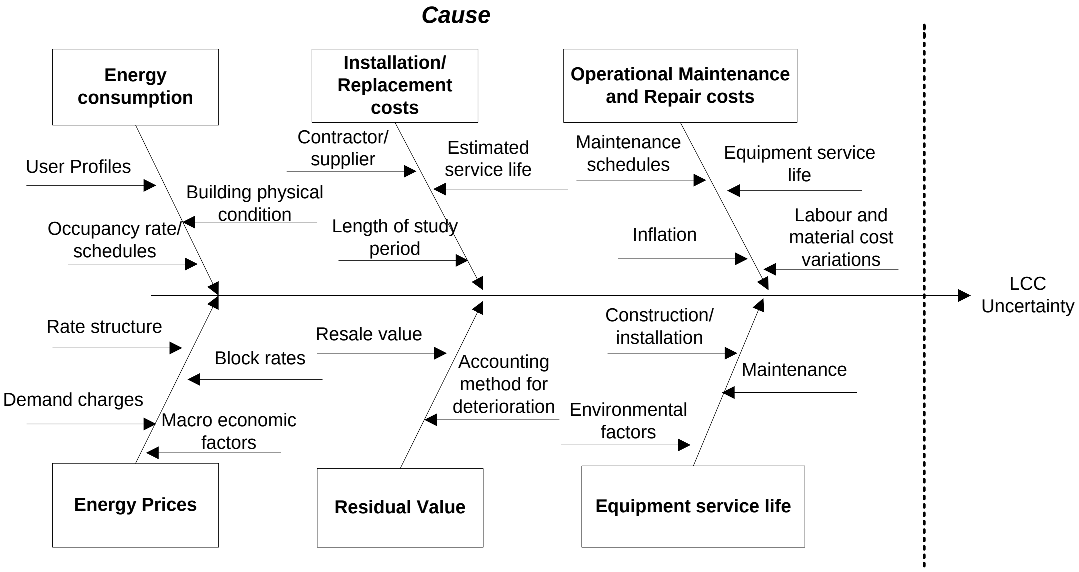


Figure 5-2: LCC uncertainties in energy retrofits (Ruparathna et al. 2017b)

Energy retrofitting is a popular climate action initiative adopted and promoted by various institutions around the world. LCC calculation of energy retrofits is associated with a number of uncertainties. This chapter proposes a fuzzy logic-based approach to calculate LCC that is applicable to buildings owned and operated by owners. The proposed approach integrates qualitative and imperfect data into the LCC analysis. A case study analysis was conducted for two different building retrofits to illustrate the results.

5.2 Methodology

The published literature commonly adopts probabilistic methods (e.g. Monte Carlo simulation) to interpret uncertainties associated with LCCA (e.g. ISO 15686-5:2008). Probabilistic methods are criticized for over-complexity and extensive data requirements (Zeynalian et al. 2013). Much of the LCC-related information is incomplete, vague, and imprecise. As a result, fuzzy set theory is used as an approach to account for variable uncertainties. Fuzzy logic has been used to incorporate imperfect data into LCC (Zeynalian et al. 2013; Whyte & Scott 2010). Fuzzy logic addresses limitations of the probability theory and is capable of handling imprecise, vague, linguistic, qualitative, and incomplete data (Ammar et al. 2013; Whyte &

Scott 2010). Plebankiewicz et al. (2015) noted that fuzzy logic alleviates numerous problems encountered in probabilistic methods (Plebankiewicz et al. 2015). Shaheen et al. (2006) established that comparable LCC results can be obtained using the Monte Carlo simulation (MCS) and a fuzzy set theory-based approach (Shaheen et al. 2007). Fuzzy set theory has commonly been used in the literature to conduct LCCA. For example, Heravi and Esmaeeli (2014) used fuzzy set theory to compare life cycle costs of pavement projects (Heravi & Nezhadpour 2014).

The fuzzy extension principle was proposed by Zadeh (1975) to determine the fuzziness in the output, y, based on a fuzzy input or a function (Ross 2005). Several methods are proposed to simplify the computation in applying the extension principle for continuous-valued functions. These methods include the Dong, Shah, and Wong (DSW) algorithm, the Vertex method, and the restricted DSW algorithm (Ross 2005). Ross (2010) claimed that the results of the extension principal, the vertex method, and the DSW algorithm are similar. Therefore, the DSW algorithm will be used for LCCA of building energy retrofits. Fuzzy set theory along with DSW algorithm has been used by many previous researchers. For example, Ammar et al. (2013) used fuzzy logic and the DSW algorithm to compare sewer rehabilitation alternatives (Ammar et al. 2013).

5.2.1 DSW Algorithm

The Dong, Shah, and Wong (DSW) algorithm is a commonly used fuzzy extension technique that adopts α -cut representation. This method differs from the vertex method by using the full α-cut intervals in a standard interval analysis. The following steps are used in the DSW algorithm:

a) Select an α value where $0 \leq \alpha \leq 1$.
b) Find the interval(s) in the input membership function(s) that correspond to the selected α-cut.
c) Use standard binary interval operations to calculate the interval for the output membership function for the selected α -cut level.
d) Repeat above steps for different α values to complete α -cut representation of the solution.

Alpha (α) cut is a crisp set derived by elements of fuzzy set A, whose membership value is equivalent to a defined threshold value ($0< \alpha< 1$). The α-cut of fuzzy set A is represented by A_α (Ammar et al. 2013). Under the fuzzy set theory, α-cut (interval of confidence) is used to calculate algebraic computations.

While used in decision making, fuzzy numbers should be transferred into crisp values (Naaz et al. 2011). Defuzzification method is used to obtain a quantifiable result out of a fuzzy set. Various defuzzification methods are used, such as Centroid of area, Bisector of area, Mean of maximum (MoM), and Smallest of maximum (Naaz et al. 2011). Mean of maximum has been commonly used as a defuzzification method (Equation 5-1), as illustrated in Figure 5-3. The following Equation 5-1 is used for defuzzification (Naaz et al. 2011).

$$Mean\ of\ maximum(MoM) = \frac{(a+b)}{2}$$

Equation 5-1

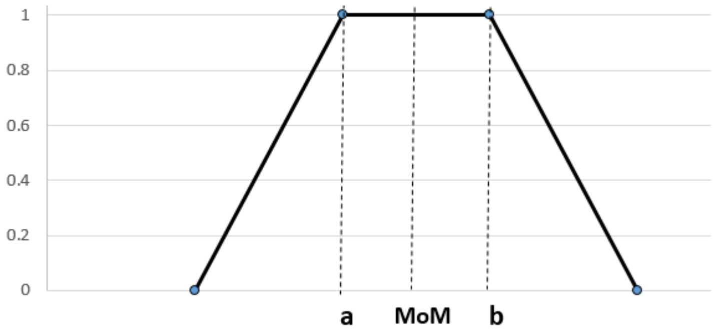


Figure 5-3: 'Mean of maximum' defuzzification method

5.2.2 Possibility

Possibility theory accounts for uncertainties arising from incomplete data (Agarwal & Nayal 2015). Possibility and necessity are the dual measures used to describe the epistemic uncertainty of possibility theory (Ross 2010). Equation 5-2 & 5-3 express possibility and necessity (Pedrycz & Gomide 2007) (X is the input fuzzy set for A_i fuzzy relations):

$$Possibility\ (A_i, X) = Sup_{x\in X}[X(x) t A_i\,(x)]$$

Equation 5-2

$$Necessity\ (A_i, X) = inf_{x\in X}\left[\left(1 - A_i\,(x)\right) s X(x)\right]$$

Equation 5-3

The possibility measure describes the level of overlap between two fuzzy sets. The necessity measure presents the level of inclusion of X in A_i (Pedrycz & Gomide 2007). Possibility distribution is numerically equal to the membership function (Tesfamariam et al. 2006). Possibility theory has been used previously to interpret fuzzy based results (Tesfamariam et al. 2006).

A fuzzy set theory-based algorithm was developed to conduct LCCA for various energy retrofits for buildings. The proposed model considers internal factors such as deterioration of components as well as capital, operational and maintenance costs, and external factors such as interest rates and inflation, which have been overlooked in the previously published literature.

LCCA requires analysis of costs and benefits associated with the selected retrofit alternatives (Estes 2011). Energy retrofits are evaluated by adding the present value of benefits (i.e. cost reduction from energy conservation in future periods*)* and present value of costs (i.e. initial investment expenditures, annual operating and maintenance costs) (Kumbaroglu & Madlener 2012). Based on Kumbaroglu and Madlener (2012) and Dhillon (2010), the Equation 5-4 was developed to analyze the LCC of energy retrofit (Dhillon 2010):

$$\boldsymbol{LCC_{ES} = IC_{PV} + NFOMC_{PV} + NRC_{PV} + RC_{PV} \pm SV_{PV} - \Delta\, EC_{PV}}$$

Equation 5-4

$LCC_{ES} = Present\ value\ of\ energy\ system\ LCC$

$\Delta\ EC_{PV} = Present\ value\ of\ annual\ energy\ cost\ saving$

$IC_{PV} = Present\ value\ of\ investment\ cost$

$SV_{PV} = Present\ value\ of salvage\ value$ (Can be a cost or benefit)

$NFOMC_{PV} = Present\ value\ of\ annually\ recurring\ non-fuel\ operation\ and\ maintenance\ cost$

$NRC_{PV} = Present\ value\ of\ non-recurring\ non-fuel\ and\ operation\ and\ maintenance\ costs$

$RC_{PV} = Present\ value\ of\ \ recurring\ non-fuel\ and\ operation\ and\ maintenance\ costs$

Real discount rate (i) is used to calculate the present value (PV) of future cash flows (Foster et al. 2010). Interest rate is the rate at which capital increases if invested, and inflation is the rate at which the price of commodities would increase.

i = Interest rate – Inflation rate

Equation 5-5

Present value (PV) of a future value (FV) occurring on period (n) at a discount rate (i) is calculated by (Rahman & Vanier 2004).

$$\boldsymbol{PV = \left[\frac{1}{(1+i)^{n}}\right]}$$

Equation 5-6

Present value (PVA) of annually recurring costs for n periods at discount rate (i) is calculated using Equation 5-7 (Dhillon 2010).

$$\boldsymbol{PVA = \left[\frac{(1+i)^{n}-1}{i(1+i)^{n}}\right]}$$

Equation 5-7

With fuzzy input data, Equations 5-7 were changed as equation 5-11 respectively, as follows:

$$\boldsymbol{\widetilde{LCC}_{ES} = \widetilde{IC}_{PV} + NF\widetilde{OM}C_{PV} + N\widetilde{RC}_{PV} + \widetilde{RC}_{PV} \pm \widetilde{SV}_{PV} - \Delta\,\widetilde{EC}_{PV}}$$

Equation 5-8

$$\boldsymbol{\tilde{i} = Inter\widetilde{est}\,rate\ - Infla\widetilde{tion}\,rate}$$

Equation 5-9

$$\boldsymbol{\widetilde{PV} = \left[\frac{1}{(1+\tilde{i})^{\tilde{n}}}\right]}$$

Equation 5-10

$$\boldsymbol{\widetilde{PVA} = \left[\frac{1-(1+\tilde{i})^{-\tilde{n}}}{\tilde{i}}\right]}$$

Equation 5-11

The computational algorithm illustrated in Figure 5-4 was used to conduct LCCA of energy retrofits. This algorithm incorporates 11 steps that are explained below.

Step 1 Select an innovative and proven energy retrofit technology for a building.

Step 2 Simulate and validate the considered building using energy simulation software. Estimate the impact of the retrofit on the building energy performance and identify energy saving potential of the retrofit alternative.

Step 3 Collect data related to installation cost, maintenance cost, future energy prices, disposal cost, inflation, interest rate, and service life (from literature and expert opinion).

Step 4 Identify memberships of uncertain variables from literature, and fuzzify.

Step 5 Select an α-cut value such that $1> \alpha>0$

Step 6 Find corresponding interest rate, inflation, and depreciation rates for the-α cut value.

Step 7 Find corresponding intervals for initial cost, maintenance cost, energy saving, and salvage value for the α-cut value.

Step 8 Use the DSW algorithm to calculate the membership function of LCC for the selected α-cut level using Equation 6.

Step 9 Repeat steps 5-8 for different α-cut values

Step 10 Different α-cut values for output function obtained from step 5-9 will be used to obtain complete α-cut representation of LCC of retrofit alternative.

Step 11 For decision making, defuzzify the output function (using MoM method) to determine a crisp value. This will be the uncertainty-based, predicted LCCA result.

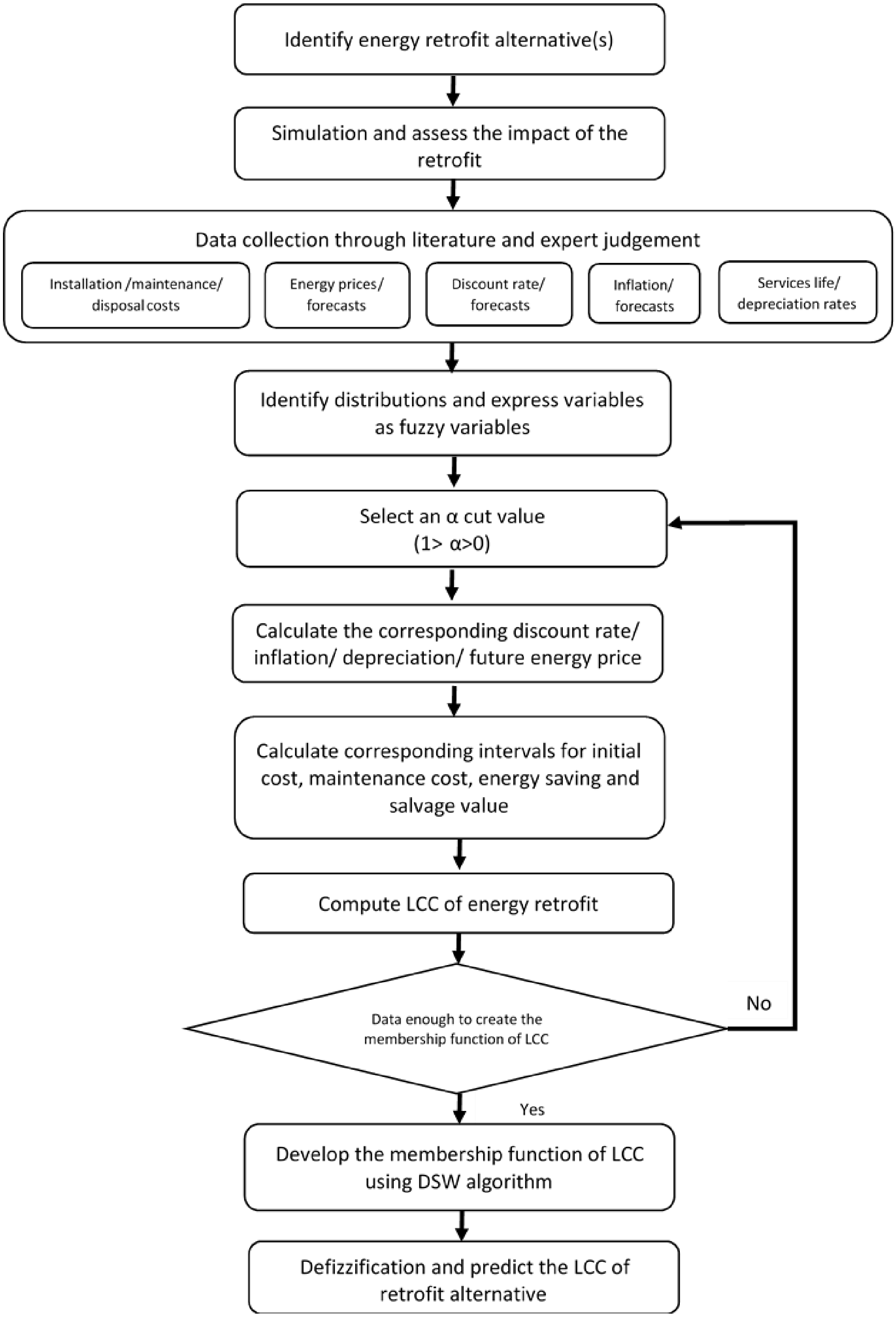


Figure 5-4: LCCA algorithm

5.2.3 Fuzzification of variables

Fuzzification creates a fuzzy variable from a crisp value. Cost uncertainty is commonly expressed as trapezoidal fuzzy numbers (Shaheen et al. 2007). Fuzzy cost ranges can be expressed in a number of formats (i.e. triangular, trapezoidal, uniform, and singleton) based on expert opinion (Shaheen et al. 2007). According to Shaheen et al. (2006), the meaning of the aforementioned fuzzy input formats are as follows:

- A triangular fuzzy number is selected when there is a most likely point between a maximum and a minimum boundary. Inflation and discount rate have been published in the aforementioned format (Innovation Science and Economic Development Canada 2014; Bank of Canada 2016).
- A trapezoidal fuzzy number is selected when the most probable range is between a maximum and a minimum boundary. Cost items (i.e. installation, maintenance, disposal costs) are commonly expressed as trapezoidal fuzzy numbers (Shaheen et al. 2007; Ammar et al. 2013).
- A uniform fuzzy number is selected when the estimate should form an interval that has minimum and maximum points. Real energy saving can be ±10 % of the simulated value (Ricker 2006). Therefore, uniform distribution is a feasible format to express uncertainty associated with energy savings.
- A crisp number is selected when it is 100% certain about a variable without any uncertainty.

Table 5-1 summarizes LCC uncertainty variables and associated uncertainty.

Table 5-1: Uncertainty variables and associated uncertainty

LCC component/ Factor	Type of uncertainty
Installation cost	Epistemic
Energy price	Aleatory
Maintenance cost	Epistemic
Disposal cost/ Scrap value	Aleatory
Energy saving	Aleatory
Service life	Aleatory
Inflation	Aleatory
Interest rates	Aleatory

5.3 Case Study

The proposed algorithm was illustrated using a case study. The case study was conducted for a public office building in the Okanagan region of BC, Canada. Energy simulation was conducted using Autodesk Green Building Studio software. Building data and assumptions considered for the building are as follows:

- Inside temperature: 21.8 degrees Celsius.
- Building Occupancy: Monday to Friday from 7:30am to 4:30pm.
- Number of building users: 90 council chambers; 45-50 staffing areas. Staffing areas are assumed to be occupied during work hours.
- Domestic hot water: Sixty US gallon electric water heater with fraction HP pump.
- Lighting system: Fluorescent fixtures retro-fitted with electronic ballasts.
- HVAC equipment: Large squirrel cage fans, electric heating elements in the unit.
- Air infiltration: 0.35 ACH.
- Space cooling: Carrier chiller with cooling coils in the air handling units.
- Building envelope construction: Bricks (R~14) with single-glazed windows.
- Wall-to-window ratio (WWR): 0.5.
- Building Orientation: 105°.
- Layout: Conventional layout with partitioned interior.

The energy model was validated using actual energy consumption data of the selected building. Since sub-metering was not available, the total building energy consumption was used for validation. Energy usage records for years 2012, 2013, and 2104 were compared with simulation results (Figure 5-5). According to the comparison, the energy model is a reasonable representation of the real building. There is a difference between actual and monitored energy data. Therefore incorporating the uncertainty associated with energy saving is important in LCCA.

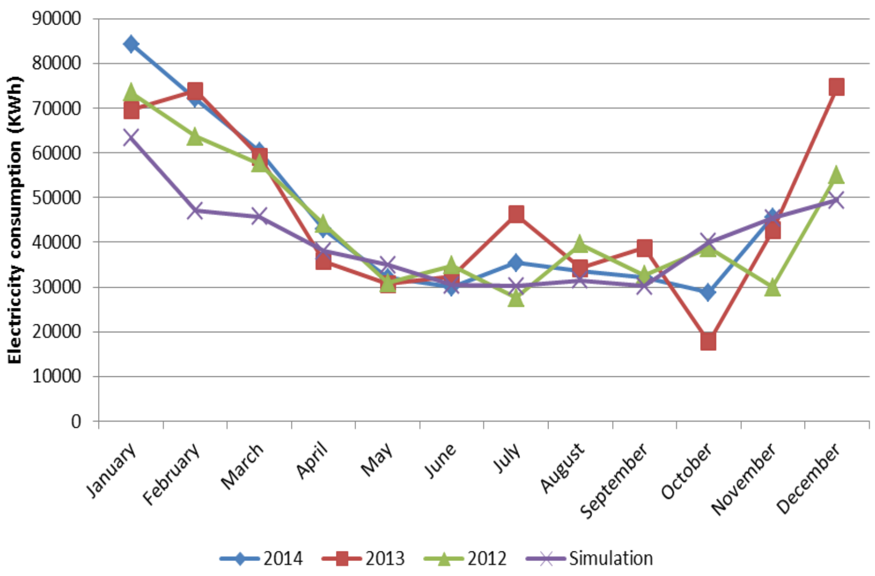


Figure 5-5: Model Validation

Two energy retrofit alternatives were considered for this study (one major retrofit and one deep retrofit) as follows (Table 5-2):

Table 5-2: Energy saving potential of retrofits

Retrofit alternative	Description	Type of retrofit	Annual energy saving (KWh)
Improving the roof insulation (Alternative 1)	*R49 insulation*	*Major*	*114063*
Installing ground source heat pumps (Alternative 2)	200 ton	Deep	249796

Cost data associated with retrofit alternatives were collected from various sources including RSMeans cost data, expert opinion, government reports, and other published literature. Cost variables were expressed as fuzzy variables.

Table 5-3 lists fuzzified LCCA variables for retrofit alternatives.

Table 5-3: Fuzzification of LCCA variables

LCC component/ Factor	Membership Function	Retrofit Alternative	
		Alternative 1	Alternative 2
Installation cost (`000 CAD)	Trapezoidal	(55,56,60,62)	(284,325,337,392)
Maintenance cost (`000CAD)	Triangular	(0,0,0,0)	(1.85,2.0,2.5, 3)
Disposal cost/ Scrap value (CAD)	Trapezoidal	(0,0,0,0)	(0,0,0,0)
Energy saving (Kwh)	Triangular	(102656,114063,125469)	(224816,249796,274775)
Service life (Years)	Trapezoidal	(50,50,80,100)	(15,25,30,38)
Energy price (CAD)	Trapezoidal	(0.042,0.0797,0.1075,0.1872)	
Inflation (%)	Triangular	(1,2,2,3)	
Interest rates (%)	Triangular	(3.5,5,8)	

LCC for various α-cut values are presented in Table 5-4.

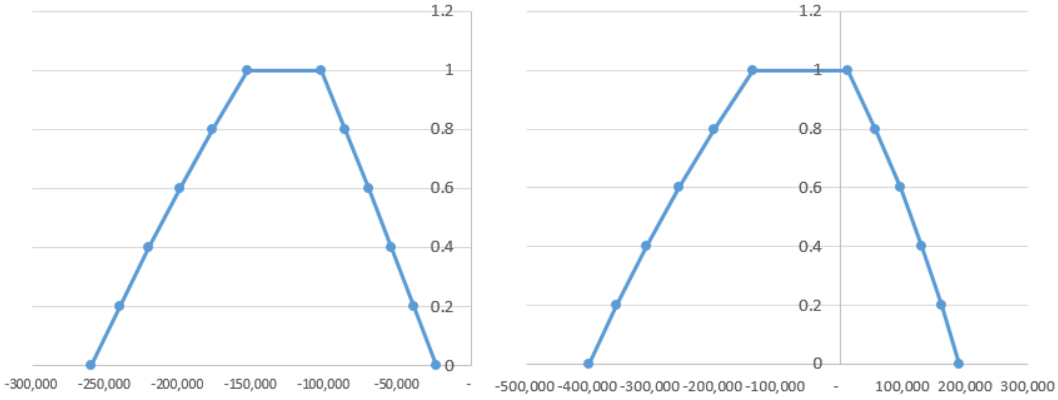
Table 5-4: LCC for various α-cut values[4]

α-cut	Alternative 1		Alternative 2	
	Low	High	Low	High
0	- 24,438	- 259,840	190,613	- 400,636
0.2	- 39,494	- 240,517	163,426	- 357,212
0.4	- 54,821	- 220,295	131,699	- 309,176
0.6	- 70,405	- 199,106	95,811	- 256,661
0.8	- 86,235	- 176,873	56,166	- 200,015
1	- 102,300	- 153,516	13,190	- 139,831

Fuzzy membership functions for LCC of energy retrofits are presented in Figure 5-6. According to Table 5-4 and Figure 5-6, there will be a cost saving from alternative 1, while there is possibility of a loss from implementing alternative 2.

---

[4] Minus (-) values indicate a financial gain.



(a) (b)

Figure 5-6: Membership functions for LCC: Alternative 1 (a) alternative 2 (b)

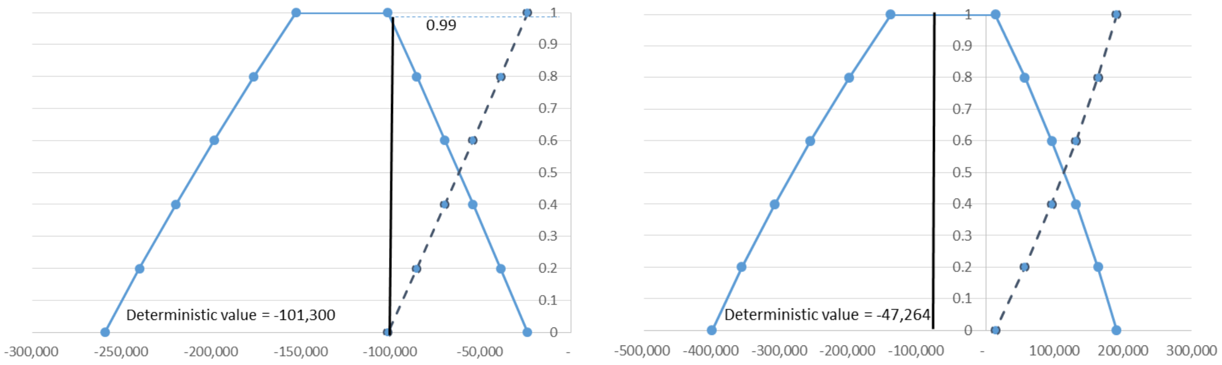
5.3.1 Deterministic Analysis

Most likely values were selected from various sources for the deterministic analysis. Table 5-5 presents values used for variables. Equations 5-7 were used for analysis. Based on Table 5-5, there will be a LCC saving from retrofit alternatives 1 and 2.

Table 5-5: Deterministic analysis

LCC component/ Factor	Alternative 1	Alternative 2
Installation cost (`000 CAD)	57,000	325,000
Maintenance cost (`000CAD)	0	2,000
Disposal cost/ Scrap value (CAD)	0	0
Energy saving (Kwh)	114,063	249,769
Service life (Years)	25	25
Energy price (CAD)	0.0797	0.0936
Inflation (%)	2%	2%
Interest rates (%)	5%	5%
LCC ($)	-101,300	-47,264

Figure 5-7 presents the deterministic result on possibility distribution. For alternative 1, possibility value is 0.99, while for alternative 2 possibility value is 1.



(a) ***(b)***

Figure 5-7: Analysis of the deterministic result

Table 5-6 presents the main LCCA results of this study.

Table 5-6: LCCA results for building energy retrofits

	Alternative 1	**Alternative 2**
Deterministic result	-101,300	-47,264
Possibility measure	*0.99*	*1*
Necessity measure	*0.01*	*0*
Defuzzified Result	-127,908	-63,320

5.4 Discussion

LCC calculation of energy retrofits is associated with a number of uncertainties. This chapter proposes a fuzzy logic-based approach to calculate LCC that is applicable to buildings owned and operated by owners. The proposed technique integrates imperfect data into the LCC analysis. A case study analysis was conducted for two different building retrofits to illustrate the results.

LCC of two energy retrofit alternatives - a major retrofit and a deep retrofit – were assessed for an office building using the proposed fuzzy-based LCCA method. The results obtained through the fuzzy-based method were compared with LCC results derived using the deterministic calculation method.

Output membership functions for two retrofit alternatives depict a significant variation in LCCA results. Output membership function of LCC savings from insulating the roof ranges from CAD 102,300 to 153,516 with a membership value 1. Moreover, membership of LCC from deterministic analysis (a saving of CAD 101,300) has a 0.99 membership to the output membership function. Hence, possibility measure of obtaining the results of deterministic LCCA result is 0.99. The fuzzy-based method reveals that it is possible to achieve higher LCC savings from insulating the roof than what was calculated by the deterministic method. This information is useful in comparing two competing alternatives.

The LCC of a geothermal heating system ranges from CAD 13,190 to -139,831 with a membership value of 1. Therefore, LCC of the geothermal heating system could be cost (loss) or savings. LCC calculated from deterministic analysis reveals that there would be LCC savings of CAD 47,264, which has full membership to the output membership function. Using this value in decision making can be erroneous, since there is a possibility of an economic loss for the building owner. The building owner has minimal control over most parameters associated with the LCC. The building owner could adopt financial risk mitigation measures to mitigate this risk (e.g. hedging). However, the objectives of adopting energy retrofits are multifaceted (e.g. economic gains, GHG reduction). Hence, this risk of economic loss could be compared with the benefits to obtain the optimal alternative.

Output membership function should be defuzzified for final decision making. Similar to the deterministic result, the defuzzified result indicates that both insulating the roof and using a geothermal heating system are financially viable. Moreover, LCCA results showed that there is a high discrepancy between deterministic and fuzzy based methods. The major retrofit had a 21% difference while the deep retrofit had a 33% difference. The above result can be attributed to the number and extent of uncertainties associated with both retrofit alternatives. This discrepancy could significantly affect the final decision, especially if the building owner is planning to obtain an optimal decision based on cost factors, GHG emissions, and energy consumption.

Considering the parameters for LCCA to be deterministic is not a valid assumption in practical situations (Ammar et al. 2013). Significant cost variances (i.e. cost estimate verses actual cost) can be observed during various stages of the life cycle of a construction/retrofit project. The results of the proposed approach should ideally have been validated by comparing it with the monitored LCC of a retrofit over its project life cycle. This was not possible due to unavailability of data. Previous studies have identified that the cost variance during the conceptual design stage can be -20 % to

+30% (Creese & Moore 1990; Canadian Construction Association 2012). Since LCCA includes estimated costs occurred in installation, operation, and disposal stages, cost variance can extend over a wider range. Proposed LCCA incorporates uncertainties associated with the LCCA parameters throughout the service life, providing a detailed illustration of the LCC. However, this result is heavily dependent on data accuracy and how well future uncertainties can be incorporated.

LCCA allows decision makers to analyze capital investments where high initial costs could be traded for anticipated future cost reductions. LCCA provides an improved assessment of long and short-term economic impacts of investments, compared to the conventional methods that only consider initial costs or short-term operational costs. Moreover, LCCA is particularly suitable when comparing alternatives with differences in parameters such as initial investment costs, OM & R costs, energy saving potentials, and service lives. The proposed method helps to incorporate the above-mentioned factors into the analysis.

The reviewed literature lists a multitude of issues related to LCC calculations with reference to constructed assets. These issues include indecisive costs that should or should not be included, evaluation methods, transparency of the process, lack of details in the pre installation stage, predicting service life, and shortage of experts to conduct LCC (International Organization for Standardization 2007). The proposed method provides a reliable LCC estimation approach for building owners. The ability of the proposed approach to incorporate vague and incomplete data into LCCA eases the challenges associated with cost data scarcity and data uncertainty.

Selecting the most probable value (deterministic method) for a variable assumes that the value is certain. This assumption is not realistic in the given context. Using trapezoidal fuzzy numbers suggests that even the most probable value is uncertain. The proposed LCC approach uses fuzzy set theory to account for parameter uncertainty. Unlike in probabilistic methods, fuzzy logic does not require excessive data and can integrate expert judgement, which is another unique feature.

This technique is sensitive to several data uncertainties associated with LCCA (i.e. installation cost, operation cost, energy rates, energy savings, discounting rate, and service life). The fuzzy based analysis revealed a wide range of possible LCC values for each retrofit alternative. This range can be narrowed by using more accurate data. Cost data from expert opinion and literature could be fed into the model. A sensitivity analysis can be used to illustrate the impact on LCC from external uncertainties such as peak rates and seasonal rates in energy prices.

LCCA results should not be the sole factor considered in decision making. LCCA studies for building energy retrofits should also consider service life of the new components and the remaining service life of the building. Moreover, scheduled major renovations in the near future need to be investigated. Combining deep energy retrofits with major renovation projects would reduce several costs, while minimizing the disturbance to building operations.

The proposed technique uses the real discounting rate for LCCA. Previously published LCCA studies have overlooked inflation in the analysis. Low risk interest rates identified by the Treasury Board of Canada, and 10-year government bond rates were considered the nominal interest rate range. The interest rate range was calculated based on inflation data obtained from the Bank of Canada, which plans to maintain inflation at 2 ± 1% (Bank of Canada 2016).

5.5 Summary

Conventional life cycle cost (LCC) analysis methods ignore uncertainties associated with parameters. This chapter analyzed uncertainties associated with LCC parameters in detail. A fuzzy set theory based LCCA technique was proposed for analysis of building energy retrofits. The LCCA technique was demonstrated using a public building in Okanagan, BC. Fuzzy based result was compared with deterministic approach. Even though deterministic result has a high membership to the fuzzy membership function, the possible LCC spans a wide range. Moreover, Fuzzy-based result informs about the range of possible LCC, which enables planning for adverse situations. The aforementioned range can be narrowed down by improving the precision of LCC parameters. However, much of the parameters are macroeconomic parameters that are beyond the control of the organization.

Chapter 6 Climate-Driven Multi Period Maintenance Planning Approach

A version of this chapter has been submitted to *Journal of Cleaner Production*, an Elsevier journal, as an article titled “Multi-period maintenance planning for public buildings: A risk based approach for climate conscious operation”.

6.1 Background

Eighty percent of the total energy use in the building life cycle is calculated in the operational stage (Jiang et al. 2013). Moreover, a typical building’s operational phase accounts for the highest CO_2 emissions and energy consumption of the building’s life cycle (Wu et al. 2011; Escrivá-Escrivá et al. 2012). Each building component deteriorates over time, which affects its performance (Grussing 2009a). Building retrofitting is one of the most feasible and cost-effective ways to improve the energy efficiency of a building (Wang et al. 2014a). Energy efficiency and building renovations are interrelated (Martinaitis et al. 2007). Previous researchers identified the importance of building management in maintaining and improving the energy efficiency of operating buildings (Curtis et al. 2017; Ruparathna et al. 2016). A good energy management program can contribute to the identification of malfunctioning equipment at initial stages, and consequently could reduce significant amounts of carbon emissions (Jiang & Tovey 2010). Jiang and Tovey (2009) mentioned that a lack of building control systems impedes buildings from meeting energy performance targets. Published literature reveals that building energy efficiency improvements have been conducted on an ad hoc basis without a systematic decision support system (Hall 2014). Moreover, published literature overlooks systematic approaches for building intervention planning which incorporate the dynamic nature of the parameters.

The operational phase is the longest of a building’s life cycle, and activities undertaken to maintain assets can lengthen or shorten the service life. In fact, the importance of building maintenance is highlighted by many researchers (Chiang et al. 2014; Min et al. 2016). Halfawy et al. (2008) identified that an integrated multi-criteria approach is needed to develop maintenance, repair, and renewal plans to optimize asset performance and LCC, and to reduce the risk of failure (Halfawy et al. 2008). The use of multiple criteria in building asset management appraisals is expensive and time-consuming, due to the uncertainty assumptions and the requirement for sophisticated tools (Martinaitis et al. 2007). The importance of intelligently appraising maintenance investments has been highlighted in literature (Martinaitis et al. 2007). Importance of optimizing energy, GHG emissions, and life cycle cost in building management has been highlighted by several researchers (Chiang et al. 2014). Moreover, optimization should be conducted at multiple future points in time. Deterioration modelling and pragmatic building management are crucial for reducing the social and environmental impacts of buildings (Jiang & Tovey 2010).

Public sector institutions are adopting proactive and optimized solutions to sustainably manage infrastructure assets in short and long term (Halfawy et al. 2008). Chiang et al (2014) identified objectives of sustainable building management, including minimizing life cycle carbon emissions and LCC, and generating life cycle employment opportunities (Chiang et al. 2014). There is a number of challenges associated with sustainable asset management, such as increasing renewal deficits, strict environmental regulations, budget limitations for building maintenance, and deterioration of aging assets (Halfawy et al. 2008). Halfway et al. (2006) revealed that despite many commercially available software programs for municipal asset management, there is a lack of software that focuses on the renewal of assets. The same authors further reported that a lack of standardized models for deterioration, risk prioritization and optimization models are the main constituents of these problems. A lack of reliable data is another associated challenge (Halfawy et al. 2008). Lee et al (2015) stated that identification of the most cost-effective energy retrofits for a building is a major challenge (Lee et al. 2015a). Even though asset management of civil infrastructure systems has been commonly used by public sector entities, there are numerous challenges in applying the same management practices for buildings (Grussing 2013).

Proactive operational maintenance of existing buildings can enhance the energy performance of the buildings (Min et al. 2016). The determinants for a solid facility investment strategy are lowering life cycle costs, improving performance, and managing risk (Grussing 2009a). Key features of an asset management system are objectivity, repeatability, and affordability (Grussing 2009a). Timely interventions could avoid accelerated deterioration in later stages (Grussing 2009a). As a solution to the aforementioned issues, it is important to establish sound asset management practices. Effective asset management systems require the evaluation of building component deterioration, identification of effective condition monitoring methods, forecasting deterioration and resulting maintenance expenditures, and decision making considering risk, cost and sustainability throughout the life cycle of assets.

This chapter presents a multi-period maintenance planning approach to manage public buildings by prolonging service life while maintaining a target condition rating, and more importantly, incorporating the dynamic nature of the parameters. This framework enables managing the condition of aquatic center buildings, evaluating solutions, and planning for long-term response strategies. This research would assist planners and decision makers in effective resource allocation and capital investment by providing an optimized building management plan. This research would also contribute to the implementation and management of energy efficiency improvements in public buildings to ensure environmental protection, improved building physical condition and reduced lifecycle cost. This is a complete decision support method that determines the optimal course of action for a stipulated performance level at the lowest LCC. The proposed approach is demonstrated using a case study for an operating aquatic center building in Okanagan, BC. Building and facilities managers would achieve aforementioned benefits from applying the proposed method for their buildings.

6.2 Methodology

Figure 6-1 illustrates the methodology adopted in this research. As illustrated in Figure 6-1, the proposed asset management methodology incorporates five phases. Each phase is explained in detail in following sections:

Phase 1: Identification of components and deterioration modelling
Phase 2: Risk-based prioritization
Phase 3: Scenario development
Phase 4: Multi-period maintenance planning based on optimal cost and life cycle costing
Phase 5: Decision making based on Value of Risk

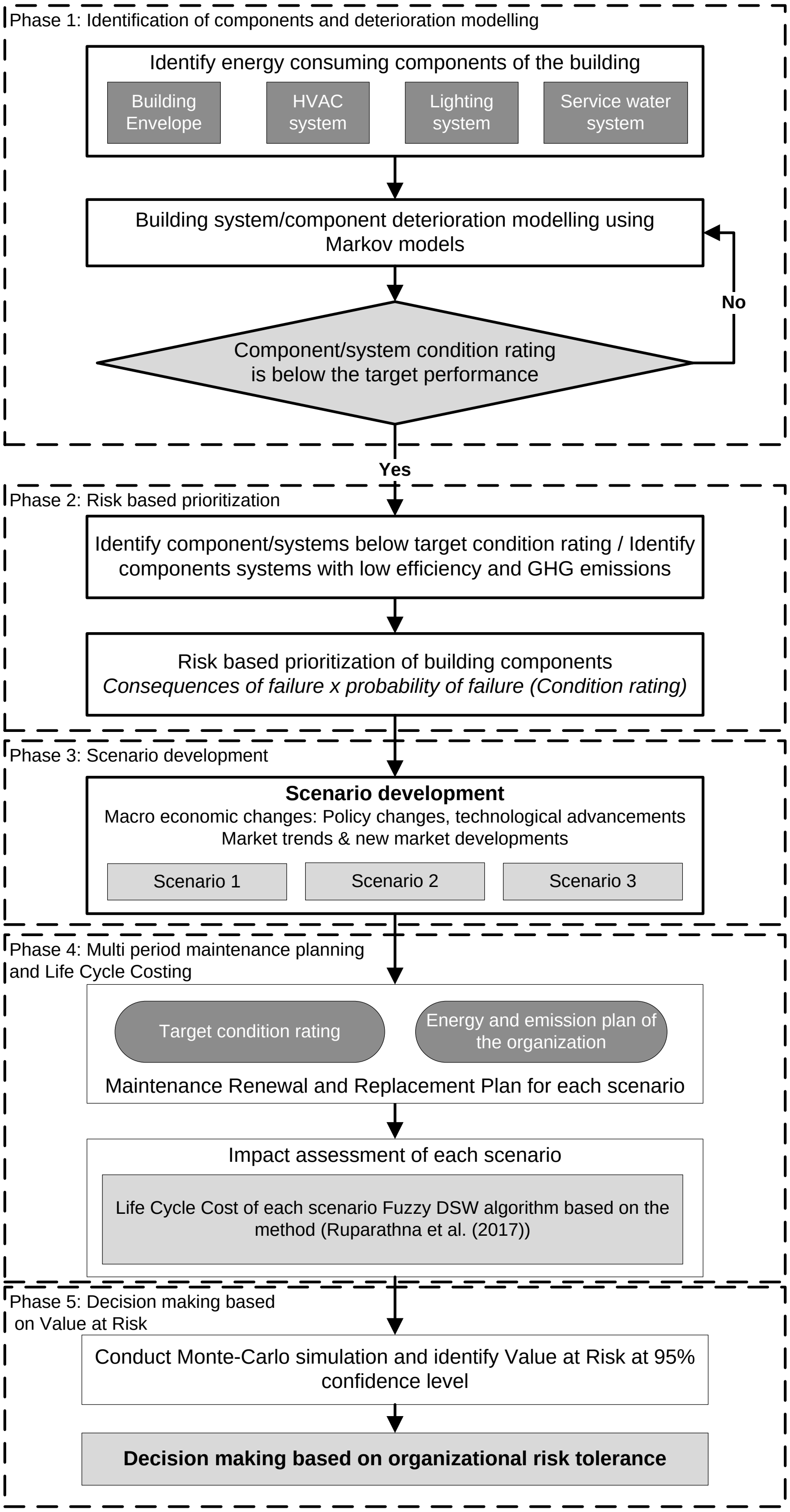


Figure 6-1: Overall methodology of multi-period maintenance planning framework

6.2.1 Identification of components and deterioration modelling

This study aims to propose planned repairs for major building systems with a climate-driven asset management perspective. Asset componentization eases the accounting of asset management expenses (Asset Management BC 2011). The use of asset componentization facilitates deterioration modelling and treatment option assessment, which is necessary for implementing advanced asset management practices (Asset Management BC 2011). The following building systems and their components have considerable effects on the energy demand of a typical building (Keshavarzrad 2015).

1. Building envelope: Wall structure and insulation, wall finish/façade, windows, doors fascia, soffit, awning, canopy, envelope ventilation components, etc.
2. HVAC system: Supply fans, air handling units, chiller, pumps, valves, compressor etc.
3. Lighting system and electrical system: Lamps, lights, fittings, distribution boards, switch board, etc.
4. Service water system: Boilers, insulation, pumps, water tanks, etc.

The listed equipment may differ according to the function of the building. Hence, it is important to identify the components based on observations and consultations with building managers. For example, a aquatic centre building will have a pool heating system, a moisture control system, etc.

6.2.1.1 Building deterioration using Markov Chain

Service life prediction is an important step in life cycle cost predictions, failure risk analyses, and maintenance planning. Deterministic, regression, stochastic, and artificial intelligence-based deterioration models have been used in the published literature. ISO proposed ISO 15686-1:2011 that establishes general principles for service life planning and a systematic framework for undertaking service life planning of a proposed building or construction work. This standard is applicable for existing or new buildings (ISO 2011). Edirisinghe et al., (2015) combined the above standard with the Markov chain concept to propose a component based deterioration model for building components.

Markovian specification is frequently used by researchers in developing deterioration models. This method implies that the probabilistic deterioration in a given period is independent of history (Samer et al. 1997). Markov chain models describe the probability of a transition from one condition state to another over a unit of time (Scheidegger et al. 2011; Ens 2012). This approach predicts future conditions relative to present condition without considering the past conditions. A transition matrix is used to present the sequence in moving from one state to another. Markov chain analysis has been used in deterioration prediction of building envelope and electro-mechanical systems (Edirisinghe et al. 2015; Keshavarzrad et al. 2014; El-rayes et al. 2016). Markov models have emerged from wireless communications and have been applied in various disciplines such as traffic engineering and finance. (Yin & Zhang 2000). The Markov chain process is capable of capturing uncertainty in initial condition, applied stresses, condition assessment errors, and uncertainty in the deterioration process (Morcous et al. 2003).

A stochastic process {X} is in state i_n at time t_n and in state j after next time step $t_{n+1.}$ According to Markov chain theory, probability of a stochastic process moving from state i_n to state j depends only on the initial state (i) (Edirisinghe et al. 2015). This can be expressed as a discrete parameter stochastic process (X_t) with a discrete state space as;

$$P(X_{t+1} = i_{t+1} | \, X_t = i_t \, , X_{t-1} = \, i_{t-1} \dots \dots X_1 = \, i_1 , X_0 = \, i_0)$$

$$P(X_{t+1} = i_{t+1} | \, X_t = i_t \,)$$

The probability of an element that is in state “i” to reach “j” after the next time step: P_{ij} (Transition probability) (Wang et al. 2008; Karunarathna et al. 2015; Edirisinghe et al. 2015). Hence transition matrix is where ij^{th} element would provide P_{ij}. Transitional probabilities should satisfy the following conditions (Edirisinghe et al. 2015).

$$P_{ij}>0 \ \Sigma P_{ij} \leq 1$$

Assuming the conditional probability does not change over time;

$$P_{ij} = P\{X_{t+1} = j|X_{(t)} = i\}$$

Transition probability matrix (TPM) of a Markov chain with five condition states is presented as a 5x5 matrix (Karunarathna et al. 2015):

$$\begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{21} & P_{22} & P_{23} & P_{24} & P_{25} \\ P_{31} & P_{32} & P_{33} & P_{34} & P_{35} \\ P_{41} & P_{42} & P_{43} & P_{44} & P_{45} \\ P_{51} & P_{52} & P_{53} & P_{54} & P_{55} \end{bmatrix}$$

$(C_{i(t)})$ is the probability of a component/system with condition rating i (for i = 1, 2, 3, 4, 5) after t years.

Condition rating of a component/system at time t is expressed as a condition state vector $(C_{(t)})$.

$$C_{(t)} = [C_{1(t)} \quad C_{2(t)} \quad C_{3(t)} \quad C_{4(t)} \quad C_{5(t)}]$$

Condition state at the initial state is defined as initial condition state vector $C_{(0)}$, for a new component / system (Karunarathna et al. 2015).

$$C_{(0)} = [1 \quad 0 \quad 0 \quad 0 \quad 0]$$

When initial condition state vector ($C_{(0)}$) and TPM (P) are known condition state after time t ($C_{(t)}$) can be obtained by Chapman-Kolmogorov formula (Equation 6-1).

$$C_{(t)}=C_{(0)} \text{ x } P^t$$

Equation 6-1

GHG emission reduction levels would be demonstrated using five performance levels established based on organizational policies. Similar to condition rating, the GHG emission reduction level (GHGR $_{i(t)}$) is the probability of energy consumption and GHG emissions reduction by i (for i = 80%, 50%, 33%, 17%, 0) after t years. The GHG emission reduction level of system at time t is expressed as a condition state vector ($C_{(t)}$).

$$GHGR_{(t)} = [GHGR_{1(t)} \quad GHGR_{2(t)} \quad GHGR_{3(t)} \quad GHGR_{4(t)} \quad GHGR_{5(t)}]$$

GHG emission reduction from the base year at the initial state is defined as initial GHG emission state vector $GHGR_{(0)}$. BC has set 2007 as the base year for GHG emission reduction targets. Hence, GHG emission reduction levels can be established based on current performance and organizational targets (Karunarathna et al. 2015).

$$GHGR_{(0)} = [0 \quad 0 \quad 0 \quad 1 \quad 0]$$

When initial condition state vector ($GHGR_{(0)}$) and TPM (P_{GHGR}) are known, the GHG emission reduction state after t time ($C_{(t)}$) can be obtained by Equation 6-2.

$$GHGR_{(t)} = GHGR_{(0)} \text{ x } P^{t}_{GHGR}$$

Equation 6-2

6.2.2 Risk-based prioritization

Aging infrastructure and funding shortages are the main problems faced by municipalities (AbouRizk et al. 2005). To address the above challenges, municipalities are prioritizing infrastructure classes based on the potential of failure. Similar approaches can be adopted for buildings in order to prioritize crucial components based on the risk of failure. The risk associated with building components can be measured using numerous indicators, such as complexity of the component, the impact of failure of a building component, critical components, and overall condition (AbouRizk et al. 2005). These indicators provide an unbiased and objective measure of the risk of failure with respect to the asset component. Moreover, the best value for money can be achieved under the limited available budget by focusing on the critical building components. Prioritization is based on the organizational objectives. Failure risk of building components depends on the consequence of failure and probability of failure. Equation 6-3 calculates the failure risk of each energy consuming equipment in aquatic center buildings.

$$Failure\ risk = Probability\ of\ failure\ X\ Consequnces\ of\ failure$$

Equation 6-3

Identifying probability of failure: Condition rating of a building system is used to depict the probability of failure. Condition rating would be established based on the age, energy consumption, etc. Condition ratings of building system components were adopted from Grussing et al. (2016) (El-rayes et al. 2016). Probability of failure is the inverse of the current condition rating (Table 6-1).

Table 6-1: Condition rating of building components

Condition state	Condition value	Description	Probability of failure
C1	5	Minimal or no condition loss	0.20
C2	4	Minor condition loss	0.25
C3	3	Noticeable condition loss	0.33
C4	2	Major condition loss	0.50
C5	1	Severe condition loss/near failure	1

Consequences of failure: Different levels of consequences of failure would be established for energy consuming equipment based on literature and expert interviews. The following consequences of failure were developed based on data from literature (Table 6-2) (NASA 2000; Keshavarzrad 2015).

Table 6-2: Consequences of failure

Consequence of failure	Score	Description
None	1	Failure of equipment does not have an impact on safety, health, environment or mission.
Low	2	Failure of equipment creates a minor effect on facility function.
Moderate	3	Failure of equipment creates a moderate effect on facility function. Entire function would be affected.
High	4	Failure of equipment creates high disruption to facility function. Significant delays in restoring function.
Very High	5	Failure of equipment halts facility function. Significant delay in restoring function.
Hazard*	Priority	There is a potential safety, health, or environmental impact.

Based on the failure risk rating, building components can be prioritized for maintenance. Maintenance priority levels were adopted from published literature is presented in Table 6-3 (NASA 2000).

Table 6-3: Maintenance priority levels

Emergency	Maintenance interventions when there is a health and safety risk
Urgent	Maintenance interventions when there is a risk to continuous operation
Priority	Maintenance interventions when there are project deadlines
Routine	Maintenance interventions attempted on first-come, first-served basis
Discretionary	These are maintenance requirements that are not a necessity but a desire.
Deferred	This maintenance undertaken when resources are available

6.2.3 Scenario planning

Porter (1995) identified a scenario as “an internally consistent view of what future might turn up to be”. Scenario planning is the link between the future and strategy (Lindgren & Bandhold 2009). Scenario planning has been commonly adopted by various disciplines for strategic planning due to its ability to incorporate both objective analysis and subjective interpretations. More importantly, each scenario illustrates how relevant factors affect each other under certain conditions (Schoemaker 1995). Scenarios provide a number of illustrative ranges of plausible futures rather than predicting or forecasting the future (Kang & Lansey 2013).

Explorative scenario planning enables decision making in an uncertain environment (Parkinson & Guthrie 2014). Scenario planning is distinct from other planning methods such as contingency planning, sensitivity planning, and computer simulations, as this approach limits extensive data from many states to a few. Furthermore, scenario planning enables the incorporation of innovations, new regulations, and value shifts, which cannot be handled by computer simulations. Scenario planning has been used in urban planning (Chang et al. 2015), water system planning (Kang & Lansey 2013; Kang & Lansey 2014; Scholten et al. 2015), supply chain risk assessments

(Thekdi & Santos 2016), transportation planning (Schroeder & Lambert 2011), and water conservation planning (Wang et al. 2013).

Developing the scenarios is the most important step in scenario planning (Kang & Lansey 2014). Scenario construction requires comprehensive discussions and input from key stakeholders and experts (Kang & Lansey 2014). Previous authors have adopted various methods for scenario planning. This study used the method steps proposed by Schoemaker (1995) and Kang and Lansey (2014) in constructing scenarios (Kang & Lansey 2014; Schoemaker 1995).

i. Define the scope
ii. Identify key stakeholders
iii. Identify key trends
iv. Identify key uncertainties
v. Construction initial scenario themes
vi. Check for consistency and plausibility
vii. Develop learning scenarios
viii. Identify research needs
ix. Develop quantitative models
x. Evolve toward decision standards

The sequential approach listed above enables planning for most possible future situations. Expert input was sought to validate the plausibility of scenarios.

6.2.4 Multi-period maintenance planning and life cycle costing

Deterioration of identified building components can be modelled using Markov chain deterioration. Microsoft Excel platform was used to develop the model. Standard operating conditions were assumed, and three different maintenance alternatives (do nothing, repair, and replace) were considered. A maintenance plan for each building system was determined by minimizing the life cycle cost for the specified minimum condition rating and GHG emissions reduction. A maintenance plan for the building was determined by combining the maintenance plans for all building systems.

The fuzzy-based LCCA method proposed by Ruparathna et al. (2017) was used to calculate the detailed LCC of the capital plan. Ruparathna et al. (2017) used fuzzy DSW algorithm to calculate the life cost of building maintenance approaches. Fuzzy logic is a powerful approach used to incorporate uncertain and incomplete data into detailed analysis. Moreover, fuzzy logic has been commonly used in LCC analyses in published literature. Equation 6-4 was used to calculate the LCC of the maintenance strategy.

$$LCC = \sum (Net\ present\ value\ (NPV)\ of\ maintenace, repair\ and\ replacements) \\ - \sum NPV\ of\ energy\ cost\ savings\ from\ repair\ and\ replacements$$

Equation 6-4

6.2.5 Decision making based on Value of Risk

Value at risk (VaR) has been a popular risk-based decision criteria in various disciplines (Mishra et al. 2013a) . VaR depicts the maximum amount of money that could potentially be lost for a defined probability and time horizon (Dempster 2002). VaR has been used for infrastructure investment decision making. Mishra et al. (2013) used VaR for transportation infrastructure investment decision planning (Mishra et al. 2013b). Parkinson and Guthrie (2014) proposed a VaR framework for building energy performance capital budgeting (Parkinson & Guthrie 2014). VaR is the quantile of estimated distributions of profit/loss for the specified time period (Mishra et al. 2013a). A VaR calculation follows following steps (Choudhry 2013).

i. Determine the time horizon over which potential loss should be estimated
ii. Select the degrees of certainty required to estimate the VaR
iii. Create a probability distribution of the likely returns for the investment in focus
iv. Calculate the VaR estimate that is chosen for the confidence level chosen in step 2

Monte Carlo simulations enable the use of actual historical distribution in the VaR calculation (Choudhry 2013). Hence, a historical simulation method was used in this study.

6.2.6 Monte Carlo Simulation

Monte Carlo simulation (MCS) is a mathematical model of a real system simulated for large numbers of times using random samples (Osman 2005; Thomopoulos 2012). MCS has been used in various fields, such as warfare, business, engineering, science and finance (Thomopoulos 2012).

Particularly, MCS has been commonly used for risk analysis in construction management (Sadeghi et al. 2010). The advantages of using MCS in risk management includes the lack of necessity for sophisticated mathematical knowledge, the availability of computer software for processing, mutually independent iteration results, and reliable and realistic results (Vose 2000; N. Wang et al. 2012).

The @Risk, educational version was used to conduct the MCS. The membership function of LCC was determined using the approach proposed by Ruparathna et al. (2017), and was used to determine the probability distribution function of the life cycle cost of the operational scenario. Ruparathna et al. (2017) proposed a fuzzy DSW algorithm to account for uncertain data, which will be used to calculate the membership function of the LCC of the maintenance plan. Ten thousand iterations were simulated to obtain the cumulative distribution function of alternative future scenarios. A ninety-five percent confidence level was selected to obtain the VaR.

6.2.7 Obtaining probability density function (PDF) from membership function

Yoon (2008) used linear transformations to convert membership function to a PDF (Yoon 2008). According to the previous author, probability of a fuzzy event is proportional to the membership function ($\mu_{(A)}$). Hence,

$$f_1(x) = C_1 \mu_A(x)$$

Equation 6-5

C_1 is a relative constant value that satisfies the condition that the area under the continuous probability function is equal to one. Figure 6-2 illustrates the transformation process of the trapezoidal membership function to the PDF. Though the original shape of the membership function is proportionally lost, the converted PDF is retained in the domain of X variables.

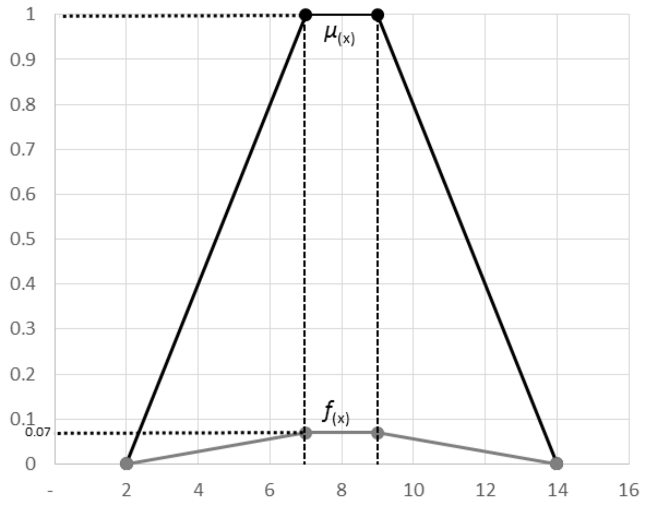


Figure 6-2: Transformation into proportional probability distribution

6.3 Case Study

The proposed methodology was demonstrated using a case study for an aquatic center building operating in Okanagan, BC, Canada. The selected energy consuming systems are as follows.

- Lighting and electrical systems
- Building HVAC system
- Building envelope

The current condition value was identified based on observation and with reference to Table 6-1, and are presented below (Table 6-4).

Table 6-4: Condition rating of the component

System	Condition rating
Lighting and electrical systems	4
Building HVAC system	4
Envelope	3

Based on published reports, capital asset plans can have a timespan as long as 20 years. The current year was considered as the base year. Hence, a 20-year period was selected for building maintenance planning. In asset management, common alternatives are do nothing, repair, and replace (AASHTO 2011; Ettouney & Alampalli 2012). Hence, the aforementioned maintenance alternatives were considered in developing the plan.

Routine Maintenance : A do-nothing policy implies that no significant rehabilitation is done to the facility, and the condition deterioration continues until the time at which the facility is abandoned. Routine maintenance will be conducted for the building.

Repair: The repair alternative will enhance the building systems to achieve a higher condition rating (below the highest condition rating).

Replace: The replace policy will replace the building system components considering future technology changes and organizational targets.

The following TPMs were used to model the performance (condition rating and GHG emission reduction) of building systems (Grussing 2015).

Regular maintenance: HVAC

$$\begin{bmatrix} 0.76 & 0.18 & 0.05 & 0.01 & 0.00 \\ 0 & 0.47 & 0.33 & 0.16 & 0.04 \\ 0 & 0 & 0.31 & 0.44 & 0.25 \\ 0 & 0 & 0 & 0.37 & 0.63 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Regular maintenance: Building envelope

$$\begin{bmatrix} 0.82 & 0.15 & 0.03 & 0 & 0 \\ 0 & 0.60 & 0.30 & 0.10 & 0 \\ 0 & 0 & 0.46 & 0.41 & 0.13 \\ 0 & 0 & 0 & 0.53 & 0.47 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Regular maintenance: Lighting & electrical

$$\begin{bmatrix} 0.95 & 0.05 & 0 & 0 & 0 \\ 0 & 0.87 & 0.13 & 0 & 0 \\ 0 & 0 & 0.81 & 0.19 & 0 \\ 0 & 0 & 0 & 0.83 & 0.17 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Replace

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Repair/Rehabilitate

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

TPM for GHG emission reduction are presented below.

Regular Maintenance[1]

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Repair/Rehabilitate[1]

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Replace-Optimistic

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Replace-Most likely

$$\begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

[1] GHG emission increases from general deterioration are ignored.

6.3.1 Scenario development

Scenarios provide plausible visions of possible future alternative situations. A scenario-based approach does not provide answers, but rather raises questions related to conceivable stories used to promote thinking and debates focused on future possibilities. In long-term capital planning of buildings, the incorporation of future developments in technology, cost and institutional targets is important. Three plausible future scenarios for future planning are given below. Table 6-5 summarizes the characteristics of the energy efficiency scenarios.

Conventional World, the business as usual scenario: The National Academy of Sciences suggests that baseline energy use can be reduced by 30–35 % by 2030 (National Academy of Sciences 2009). No changes from the current trends are expected for energy demand reduction potential of energy technologies or cost of installations. Energy tariffs will increase by 30% in next 20 years. The institution will pursue current GHG emissions reduction targets (i.e. 33% GHG emission reduction by 2020). This is the business as usual scenario.

Great Transitions, a new horizon in energy efficiency: Future technology advancements would further reduce energy demands higher rate (Nadel 2015; Harder 2015). Due to advanced technology future replacements will further reduce energy demands by 40-60%, reducing 40-60% of GHG emissions from the system. Installation cost of replacements would be reduced by 25-50%. Energy efficiency after retrofits would be increased by 40-60%. The institution will pursue current long term BC GHG emission reduction targets (i.e. 80% GHG emission reduction by 2050) (US Department of Energy 2015c). This is the optimistic future scenario.

Exhausted Giant, energy efficiency innovation fatigue: Global interest of energy efficiency has faded due to macro-economic changes. Costs of energy efficiency technologies are on the rise (10-25%). Similar to Conventional World, no changes from the current trends are expected for energy demand reduction potential of interventions. Energy tariffs will increase by 30% in next 20 years. The institution will pursue current GHG emission reduction targets (i.e. 33% GHG emission reduction by 2020). This is the pessimistic future scenario.

Table 6-5: Future scenarios

	Business as usual	**Great transitions**	**The exhausted giant**
Energy saving potential of interventions	15%-25%	40%-60%	15%-25%
Installation cost of retrofits (Replacements)	0-25%	25-50% (Reduction)	10-25% (Increase)
GHG emission reduction target	33% reduction in 2020 from 2007 levels	80% reduction in 2050 from 2007 levels	33% reduction in 2020 from 2007 levels

The following constraints were established to develop the maintenance plan.

- Target system condition rating: 4
- Target GHG emissions rating depends on specific emission reduction targets of the scenario (80% reduction by 2050 or 33% reduction by 2020 from 2007 levels).

The costs in Table 6-6 were obtained from feasibility studies of swimming pool projects in Canada. Condition ratings were obtained from observation (Table 6-6).

Table 6-6: Building Information

	Building Envelope[1]	**Lighting and electrical systems**	**Building HVAC system**
Condition rating	4	4	4
Replacement cost (CAD)	1,750,000	360,000	3,520,000

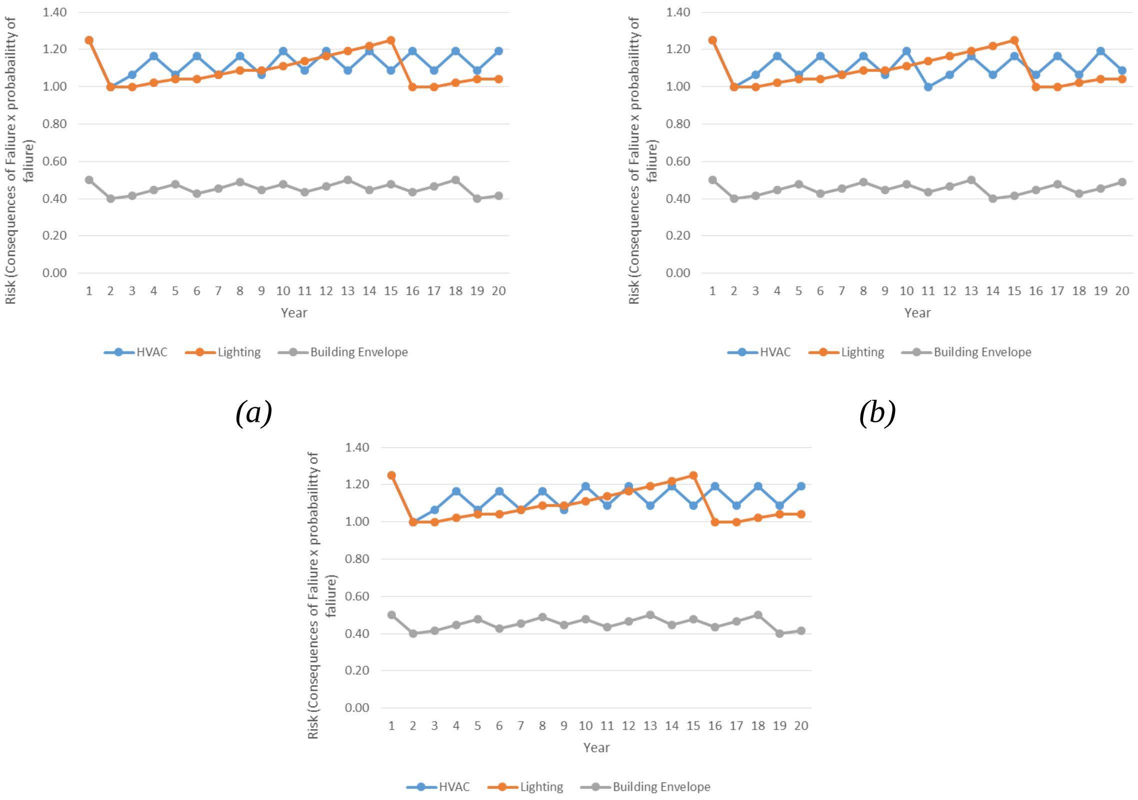
[1] *Finished and insulation of building envelope was considered*

Table 6-7 illustrates the maintenance plan for the aquatic center building. The capital plan with lowest LCC was identified.

Table 6-7: Maintenance plan for the aquatic centre building in focus

Year	Conventional World			Great Transitions			Great Transitions		
	Building HVAC system	Lighting and electrical systems	Building Envelope	Building HVAC system	Lighting and electrical systems	Building Envelope	Building HVAC system	Lighting and electrical systems	Building Envelope
1	Repair	Repair	Repair	Repair	Repair	Repair	Repair	Repair	Repair
2	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance
3	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Repair	Maintenance	Maintenance
4	Repair	Maintenance	Maintenance	Repair	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance
5	Maintenance	Maintenance	Repair	Maintenance	Maintenance	Repair	Maintenance	Maintenance	Repair
6	Repair	Maintenance	Maintenance	Repair	Maintenance	Maintenance	Repair	Maintenance	Maintenance
7	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Repair	Maintenance	Maintenance
8	Repair	Maintenance	Repair	Repair	Maintenance	Repair	Maintenance	Maintenance	Repair
9	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance
10	Repair	Maintenance	Repair	Replace	Maintenance	Repair	Repair	Maintenance	Repair
11	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance
12	Repair	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Repair	Maintenance	Maintenance
13	Maintenance	Maintenance	Repair	Maintenance	Maintenance	Replace	Maintenance	Maintenance	Repair
14	Repair	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Replace	Maintenance	Maintenance
15	Maintenance	Replace	Repair	Maintenance	Replace	Maintenance	Maintenance	Repair	Repair
16	Repair	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance
17	Maintenance	Maintenance	Maintenance	Repair	Maintenance	Repair	Repair	Maintenance	Repair
18	Repair	Maintenance	Replace	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Replace
19	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Repair	Maintenance	Maintenance
20	Replace	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Maintenance	Replace	Maintenance

Figure 6-3 illustrates how failure risk changes for different building systems over the years for a new building. As described in Figure 6-3, risk-based relative priority of a building component changes annually. However, the relative risk levels remain the same despite the scenario. This is due to the pre-established performance rating of 4, and an assumption that the consequences of failure do not change with time. Hence, in a budget-constrained institution, it is important to identify building systems with the highest risk at a specific time period to prioritize the components/systems which urgently require interventions.



(a) *(b)*

(c)

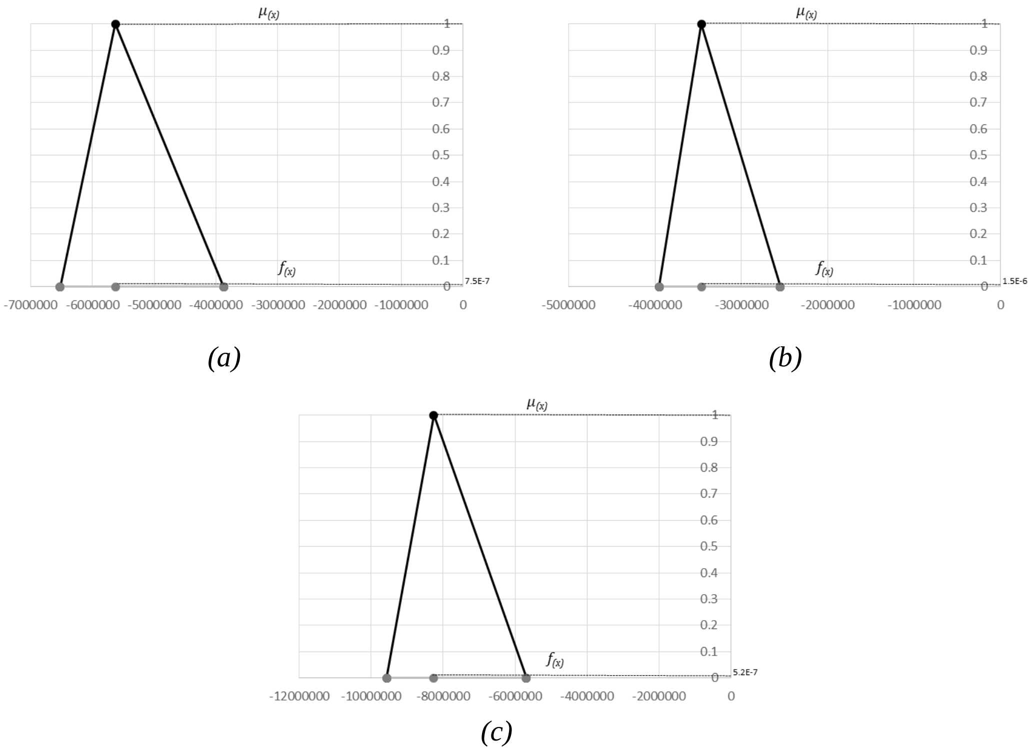
Figure 6-3: Failure risk-based prioritization of building systems for three scenarios (a) Conventional World, (b) Great Transitions and (c) Exhausted Giant

Regular infrastructure maintenance costs have been defined using various methods. With reference to the published literature, 2%-5% of the replacement cost was used for regular maintenance, and repair costs can range from 10%-25% depending on the condition rating (Wireman 2004; The World Bank 2005). Triangular distributions have been commonly used to incorporate uncertainties in LCC, and to define the cost of maintenance alternatives. Table 6-8 presents uncertain cost data obtained from published literature.

Table 6-8: Uncertainty of cost data

		Building Envelope	**Lighting and electrical systems**	**Building HVAC system**
Regular maintenance (As percentage of replacement cost) (Wireman 2004)(The World Bank 2005)		2-3.5-5	2-3.5-5	2-3.5-5
Repair/rehabilitate (As percentage of replacement cost) (Wireman 2004; The World Bank 2005)		10-17.5-25	10-17.5-25	10-17.5-25
Replacement cost - *In thousands of CAD* (City of Timmins 2016; CEI Architecture Planning Interiors 2011; Phelan 2015)	Low	1,400	277	3,350
	Most likely	1,750	360	3,520
	High	2,075	490	3,700

Membership function of building LCC is based on the method proposed by Ruparathna et al. (2017), and is presented in Figure 6-4 (a) Figure 6-4 (b) and Figure 6-4 (C) illustrate the process of converting the LCC of each scenario to a membership function.



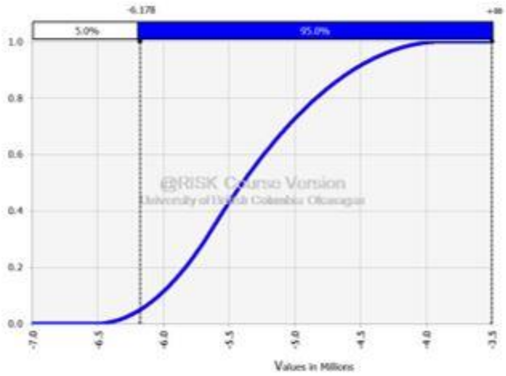
(a) *(b)*

(c)

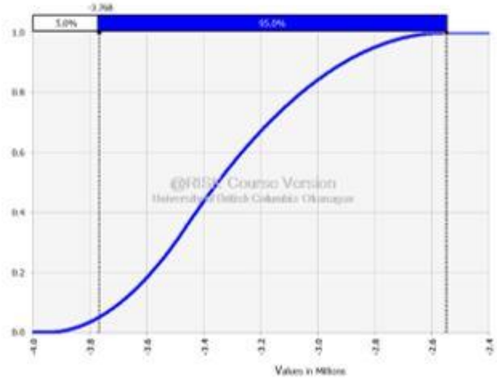
Figure 6-4: Conversion of membership function to distribution function

Figure 6-5 presents the cumulative distribution function for two LCCs and VaRs for each scenario. Based on Figure 6-5, the institution should pursue the plausible future scenario which minimizes the potential loss for the organization. Based on the VaR, the institution should pursue Scenario 1, as it has the lowest financial risk.

Conventional World : **VaR = 6,180,000**



Great transitions: **VaR = 3,768,000**



The exhausted giant : **VaR = 9,061,000**

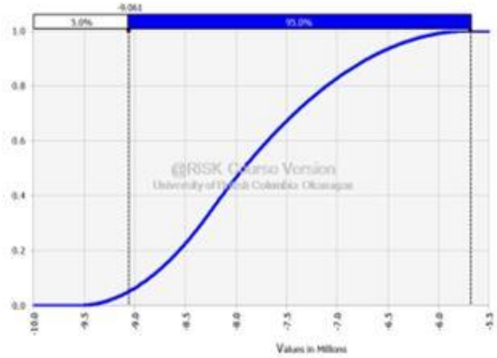


Figure 6-5: CDF and VaR for different scenarios

6.4 Discussion

This chapter proposed a risk-based multi-period maintenance planning framework for public buildings. There are several unique features of the proposed asset management framework. This framework recommends interventions based on the forecast conditions and user-defined standards of operations, prioritizes interventions based on risk, assigns funding to the highest priority items, predicts future conditions assuming the planned course of action, and predicts the future condition based on interventions and deferred maintenance. The proposed framework adopts a scenario-based approach to identify optimal multi-period maintenance plans for each scenario, eventually determining the best capital planning strategy. The VaR based scenario selection method converts the subjectivity of strategic planning into a quantifiable format. Risk-based prioritization is a unique contribution from this chapter, which enables the identification of maintenance priorities when operating under a limited budget.

This framework developed three maintenance strategies for three plausible future scenarios for an aquatic centre building in Okanagan, BC. Except in the great transitions, maintenance strategies were similar in the other two scenarios. For the 20-year period considered, there is a net cost in all maintenance strategies. The possible LCC of the scenarios spans a wide range. Based on the analysis, Great Transitions scenario is expected to result in the lowest financial risk. Therefore, the Great Transitions is the best maintenance strategy for the building in focus. The VaR associated with this strategy is CAD 3,768,000, which is 39% less than that of the conventional world scenario. VaR is the 95% confident cost expected by adopting the maintenance strategy. Analysis was conducted for three building systems (the HVAC system, building envelope and lighting system) to demonstrate this methodology. However, this method could be used for the entire building with multiple systems and components.

A unique feature of the proposed framework is its ability to incorporate future technological and economic changes into the capital planning strategy. Several methods have been adopted to account for future uncertainties associated with decision making, such as optimization and sensitivity analysis. Due to the stochastic nature of the future, optimization-based planning may not provide a realistic approach. The scenarios used in this study incorporate future cost changes, technology changes, and institutional policy changes (e.g. GHG emission targets). Scenarios were developed using a systematic method described in the literature. Moreover, expert input was sought to validate the plausibility of the scenarios. Hence, this approach provides a better decision compared to conventional optimization based approaches.

Based on the evaluation, three building systems needed to be repaired during the year 1, which requires significant financial resources. Prioritization is important when repair/replacement is needed for multiple items in a single year. Though the proposed approach incorporates a risk-based prioritization approach, it was not used in the case study since multiple repairs did not overlap in the same period. More importantly, this approach identified the years in which more budgetary allocations are required to ensure climate-friendly building operation.

VaR was used as the basis for deciding the planning strategy which enables decision making based on a specific confidence level. Different confidence levels could be selected for different scenarios based on the uncertainty. Even though there are the criticisms, VaR provides a comparable basis for selecting the planning strategy. During the capital planning process, institutions prefer to pursue a course of action that is acceptable within the risk tolerance of the organization, and VaR could fulfill this data requirement. VaR was calculated using a Monte Carlo simulation based method. This research used the LCCA method proposed by Ruparathna et al. (2017), which used fuzzy logic in calculating the LCC of the maintenance strategy. Using this approach enables the incorporation of a wider range of uncertainties associated with the LCC. The output membership function was used to determine the cumulative distribution function.

There are various deterioration models available in the literature, namely, regression models (e.g. linear regression, nonlinear regression), curve fitting models (e.g. B-Spline approximation, stochastic models), artificial neural networks and case based reasoning (Ens 2012; Nebraska Department of Roads 2011; Prozzi & Madanat n.d.; Scheidegger et al. 2011; Samer et al. 1997; Tran 2007; Morcous 2000; Morcous et al. 2002). Each method has it pros and cons with regards to simplicity, detail, and comprehensiveness. This study used Markov deterioration for deterioration modeling of building systems, as it has been commonly used as a deterioration method in literature. However, in practice, deterioration method used by an organization is determined by the organizational policy mainly for financial accounting. The objective of this study is to develop and demonstrate the proposed methodology. Furthermore, climate change could have an impact on the deterioration of building components. Consequently, prioritized building components may vary based on different condition ratings.

The findings of this chapter would support capital asset planning for public organizations which lack objective methods in their planning approach. This framework requires expert input in determining the scenarios, which is a value addition from current methods. The multi-period maintenance plan provides a maintenance strategy for building systems that affects the energy consumption of the building. The maintenance of structural components has not been studied in detail, as this aspect was considered to be beyond the scope of this research. However, combining structural deterioration with the physical condition enables a holistic and integrated approach in building maintenance. More importantly, this approach would allow cost minimization, since multiple retrofits could be implemented as packages. Each building system consists of a large number of building components. Generally, repair and replacement of building minor components would be included as routine maintenance. However, the proposed method could be used for asset management of critical building components (e.g., air handling units, chillers, boilers etc.).

This framework uses multi-period single objective optimization (minimizing the life cycle cost) to determine the maintenance plan of respective building systems. Building asset management expenditure includes both capital and recurring expenditures. However, only capital expenditure is used for capital asset maintenance. In order to provide a holistic view of the LCC, regular maintenance was included in the analysis. The cost of maintenance would influence the asset management decision. A multi-period multi-objective optimization approach can be used to maximize the GHG emissions reduction, in addition to the minimizing the LCC. In this approach, GHG emissions reduction was introduced as a constraint (i.e., as a target), which is a more practical approach since it is a part of the strategic targets of the local government.

During maintenance planning, it is important to avoid maintenance backlog. Facility condition index (FCI) is a commonly used indicator for facility management, which provides information regarding deferred maintenance for the building to avoid extensive backlogs. FCI is defined as the ratio of deferred maintenance to replacement value (National Research Council et al. 2004).

FCI could be used as an indicator to check whether deferred maintenance exceeds the anticipated level of the organization.

6.5 Summary

This chapter proposed a climate-driven multi-period maintenance planning framework for built environment. The proposed framework enables the incorporation of possible future technological advancements, cost changes and environmental demands into the decision making process. This framework assists building managers in the prioritization and planning of building maintenance interventions in order to maintain a specified physical condition while keeping pace with constantly evolving environmental standards. The framework was applied for an aquatic center building in BC, Canada. Maintenance strategies were developed for three plausible future scenarios. Finally, the scenario with least VaR was recommended as the capital planning strategy. Use of VaR provides a valid basis for selecting the least risk maintenance strategy for the building. Results of the demonstration case study provided detailed information for building maintenance planning by recommending the most suitable interventions in specific periods. This information will support the development of a climate-conscious capital asset planning strategy for a local government.

Chapter 7 Investment Planning for Net Zero Emission Buildings (NZEB)

A version of this chapter has been published in *Cleaner Technologies and Environmental Policy*, a Springer journal, as an article titled **“**Rethinking net zero emission building investment planning”(Ruparathna et al. 2017c).

7.1 Background

There are various initiatives in the building industry to mitigate climate impacts, such as net-zero energy buildings, net-zero emission buildings, net-zero source energy buildings and net-zero cost buildings (Torcellini et al. 2006). Aforementioned buildings adopt energy efficiency features to reduce energy demand, and supply the remaining demand via renewable energy sources (Steven Winter Associates Inc. 2014). Net-zero emission buildings (NZEB) use emission free energy and supplied from on-site renewable energy generation (US Department of Energy 2015b). The advantages associated with the aforementioned buildings include minimized environmental footprint, minimized operations and maintenance costs, and enhanced system reliability and energy security (US Department of Energy 2015b). NZEB was identified as a key route for ambitious energy efficiency targets of BC (Frappé-Sénéclauze & Kniewasser 2015).

Similar to net-zero energy buildings, NZEB is a new concept. Improving the energy efficiency is the priority in reducing the building energy consumption to achieve net-zero energy/emissions status. The remaining energy demand should be supplied by renewable energy sources that are economical, readily available, and replicable (Steven Winter Associates Inc. 2014). For NZEB, supply could be from on-site or off-site renewable energy sources (Torcellini et al. 2006). A building that is situated in an area that has a clean electricity grid (e.g. hydro, nuclear) can achieve net-zero emissions status with lesser configurations compared to a similar building which is powered from fossil fuel based electricity grid (Torcellini et al. 2006). Hence regional grid emission factor is an important consideration in NZEB (Torcellini et al. 2006).

Despite the availability of a large number of energy retrofits, methods to analyze and identify the most suitable retrofit remains a challenge (Asadi et al. 2014b). Decision making associated with energy efficiency investments are not straight forward (Hertzsch et al. 2012). Various appraisal methods have been used for evaluating building energy retrofits (Martinaitis et al.

2007). Though energy simulation software can provide an approximate estimation of the impacts of energy retrofitting, the use of simulation software is limited to trained professionals (Chidiac et al. 2011). Building energy consumption, GHG emissions, and life cycle costs have complex interactions when identifying the optimal investment limit for retrofits. Energy, environment, economy, and the timing of retrofits are the main decision criteria in building management. Since various retrofits are available for GHG emissions mitigation and operational cost reduction, it is important to determine the optimal trade off (Chiang et al. 2014). Conducting a reliable analysis of the interactions between building condition, environment, and annual energy consumption is cumbersome task (Peng et al. 2014).

It is important to select the optimal retrofit option in a timely manner (Asadi et al. 2014b). Moreover, the ambiguity about future benefits is a main challenge for investments in energy retrofits projects (Malatji et al. 2013b). Time-dependent simulations are required to identify the energy-saving targets, and to provide a justification for selecting retrofit alternatives (Peng et al. 2014). The use of integrated and comprehensive computer models can foster revolutionary work practices, superior environmental performance, and significant cost savings in FM (Yu et al. 2000).

Budget limitations compel the public to seek innovative decision making methods in obtaining the best value for allocated funds. In building retrofitting, it is important to identify the retrofit that achieves the optimal reduction in energy consumption, GHG emissions, and operational cost (Wang et al. 2014b). However, in practice, optimization of building energy retrofits considering multiple factors have been overlooked by the industry (Rysanek & Choudhary 2013). This chapter proposes an energy retrofit investment planning approach for asset management of public aquatic center buildings, by integrating energy-GHG-life cycle cost nexus. First, a comprehensive investment planning approach was proposed for NZEB. Second, an aquatic centre building that operates in Canada was used as a sample model for proof of concept. Innovative and proven building retrofits were identified and the relationships between energy consumption, GHG emission, and investment were analyzed to identify the optimal investment. Third, the impacts of varying climates and tariff schemes on the optimal retrofit were analyzed for various provinces in Canada to determine the optimal net-zero emission investments (NZEI).

7.2 Methodology

A sequential process was adopted in identifying the optimal investment and planning method for building energy retrofits (Figure 7-1). This generic framework could be adopted for different building types.

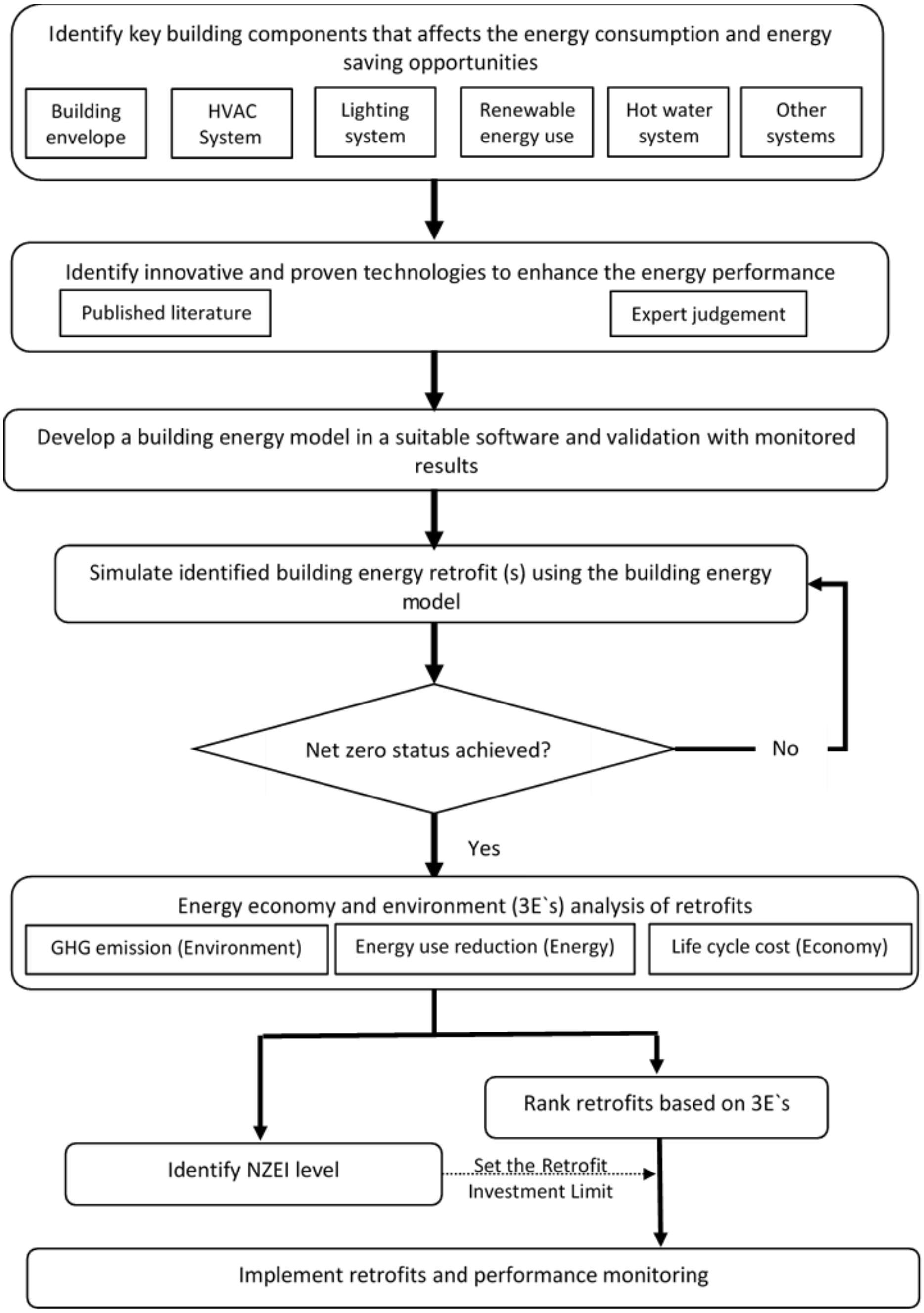


Figure 7-1: Energy retrofit planning approach

7.2.1 Ranking energy retrofits

The objective of energy retrofits is to decrease the annual cost savings, decrease energy consumption, and decrease GHG emissions. Hence, retrofit alternatives were ranked according to the 3Es (energy, economy and environment). Energy simulation and LCC analysis results for each retrofit were normalized to obtain a score for each parameter. Scores for 3Es were combined using the weighted sum method to obtain a final score. Equal weightings were considered for 3Es. The final score was used to rank the considered energy retrofits.

7.2.2 Investment planning for NZEB

The results of the energy simulations for retrofit alternatives were used to determine energy cost reduction, GHG emissions reduction, and LCC for various retrofit investments. The maintenance cost was assumed to be included in the installation cost contract. Equation 7-1 to Equation were used to calculate the aforementioned values.

$$\begin{aligned} &Annual\ operational\ energy\ cost\ reduction \\ &\qquad = Annual\ initaial\ energy\ operational\ cost \\ &\qquad - \sum_{i=1}^{n} (Energy\ reduction\ from\ retrofit_i \times Provincial\ energy\ rate) \end{aligned}$$

Equation 7-1

$$\begin{aligned} &Annual\ GHG\ emission\ from\ the\ facility \\ &\qquad = \sum_{i=1}^{n} (Energy\ consumption\ reduction\ from\ retrofit_i \\ &\qquad \times Emission\ factor\ for\ the\ region) \end{aligned}$$

Equation 7-2

$$\begin{aligned} &Annualized\ LCC_{ES} \\ &\qquad = \text{Equivalent annualized cost of initial cost} + Annual\ Operational\ cost \\ &\qquad + Annualized\ maintenace\ cost \end{aligned}$$

Equation 7-3

Equivalent annualized cost (EAC) of the initial investment is calculated using Equation 7-4 (Sasmita 2010).

$$EAC = initial\ investment \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right)$$

Equation 7-4

Where i is the discounting factor and n is the number of periods.

7.3 Case Study

A sample aquatic centre building operating in South Okanagan, BC Canada was used for demonstration purposes. The identified system was modelled by using the Design Builder V4 software environment. The building details collected from drawings and expert input are presented in Table 7-1.

Table 7-1: Building parameters

Building parameter		**Details**
Total floor area		~9234m^2
Pool area		~1925m^2
Length		69.43m
Building height		12.65 m
Ground Floor		4.115m
Monitored energy use	Electricity	8196 GJ
	Natural Gas	6017 GJ

Figure 7-2 depicts a schematic view of the Design Builder model used in this study. The model was validated using the annual energy consumption data (Shown in Figure 7-2). The annual monitored energy values were compared with estimated values from the energy model.

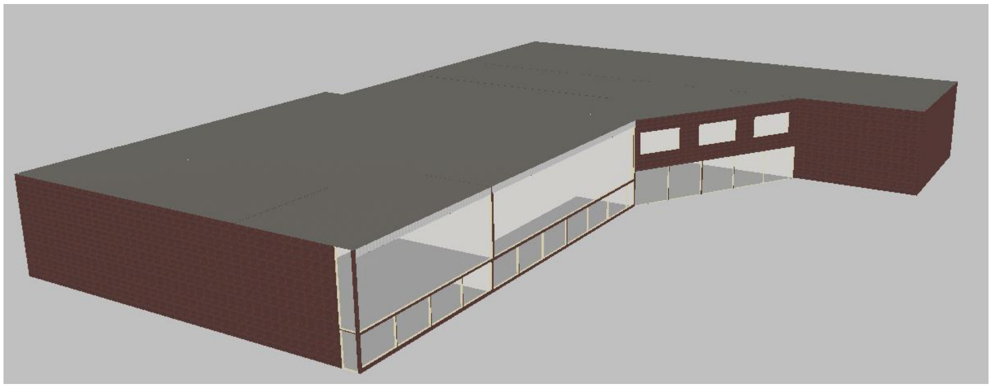


Figure 7-2: Schematic of Design Builder energy model

7.3.1 Energy retrofits for aquatic centre buildings

Published literature was used to identify the energy retrofits for aquatic centre buildings (Table 7-2). These retrofits have been successfully used in various aquatic centre buildings in Canada. The identified energy retrofits were simulated in the Design Builder building energy simulation software. The simulation results are presented in the Appendix D.

Table 7-2: Proven retrofits for aquatic centres

Building Envelope	R1	Increase the insulation of the roof	(CEI Architecture Planning Interiors 2011)
	R2	Replace front glazing with a double-glazed system.	(CEI Architecture Planning Interiors 2011; Sydney Water 2011)
	R3	Increase the insulation of walls	(CEI Architecture Planning Interiors 2011)
Lighting System	R4	Change the lighting to LED (Except swimming pool areas)	(Stantec Consulting Ltd. 2008; Township of Esquimalt 2013)
	R5	PV electricity for the building	(Sydney Water 2011; City of Toronto 2014)
	R6	Daylight sensing lighting controls	(City of Toronto 2009)
Pool heating	R7	Geothermal pool heating system	(International Energy Agency 2013)
Hot water supply	R8	Use of solar preheater	(Sydney Water 2011)
	R9	Solar hot water systems	(Sydney Water 2011; Township of Esquimalt 2013)
Building HVAC system	R10	Solar Ventilation Air Preheating	(US Department of Energy 2012b)

7.3.2 Regional analysis for Canada

The same building was simulated at various geographical locations in Canada. Details about the locations of the building, the regional electricity grids, and the tariff information are presented in Appendix E.

In order to identify the optimal retrofit investment curves for energy cost reduction, energy consumption and LCC should be identified. This step required a large number of data points to construct a graph. Hence, various combinations of the retrofits identified in Table 7-2 were considered. Microsoft Excel was used to create required data points for the analysis by using power sets. For 10 retrofits, 1024 combinations were created. For all 1024 combinations, the annualized LCC, energy consumption reduction, and GHG emission reduction were calculated using Equations 6-1 through 6-3. Current energy demand, operational cost, and GHG emissions were incorporated into the Excel model. A second order polynomial function was used for similar applications in the literature (Jafari & Valentin 2015), and this function had the best fit for the data points. Hence, a second order polynomial function was assumed for trend line. The optimal retrofit investment for net-zero GHG and energy status were calculated for various regions of Canada for assuming the same building. Microsoft Excel solver was used to solve the polynomial function obtained for LCC, GHG emission and energy cost reduction.

7.3.3 Energy analysis for BC

The energy simulation for the selected building returned the following results. Figure 7-3 compares simulation results with the monitored values. Figure 7-3 shows that the developed energy model is a reasonable representation of the building in focus.

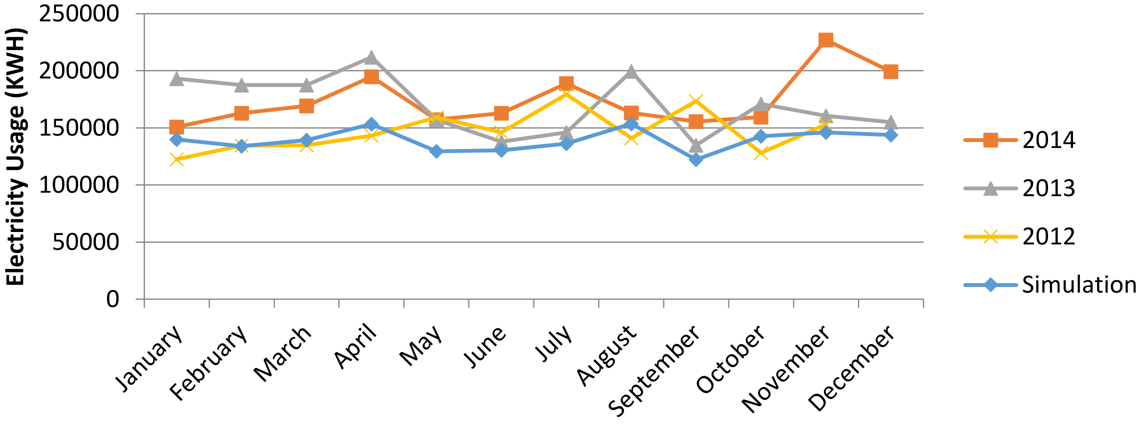


Figure 7-3: Model validation

Table 7-3 presents the values calculated for energy cost reduction, life cycle cost, and GHG emissions for Okanagan, BC. Detailed cost and energy information are included in Appendix D. Retrofits are ranked based on energy reduction, GHG emissions, and life cycle cost assuming equal weights to the three parameters. Based on the analysis, automatic lighting controls (R6) is the optimal retrofit.

Table 7-3: Energy cost reduction, GHG emission reduction and LCC for various retrofit investments (for Okanagan, BC)

Retrofit #	Energy demand reduction (GJ)	GHG emission reduction (kg CO2eq)	Annualized LCC (CAD)	**Rank**
R1	735	36,675	2085	10
R2	769	38,342	1233	9
R3	1,270	63,348	-131	3
R4	738	530	-425	4
R5	462	332	-343	6
R6	388	279	-1453	1
R7	2,451	122,250	1255	2
R8	178	8,891	-22	8
R9	350	17,455	-43	7
R10	669	33,341	-65	5

Based on Figure 7-4, net-zero emission investment (NZEI) is CAD 824,640 for the building in focus. These retrofits will achieve an annual operational cost reduction of CAD 57,737.

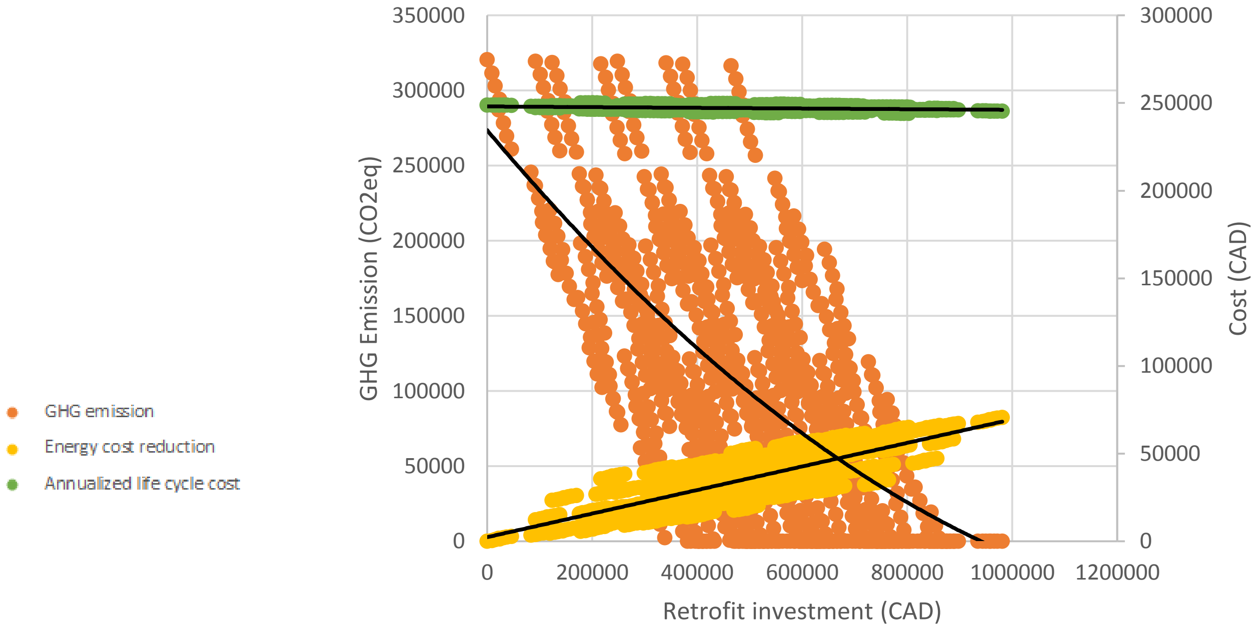


Figure 7-4: Retrofit investment analysis for BC

Therefore, in order to become a NZEB, the optimal approach is installing the retrofits R1, R2, R3, R5, R6, R7, R8, R9, R10 (Cost CAD 856,796).

7.3.4 Regional analysis

The impact regional characteristic on optimal retrofit alternatives is presented in Table 7-4. Table 7-4 depicts that optimal retrofit differ based on the provincial grid and energy tariff.

Table 7-4: Retrofit investment analysis for BC

	Energy Carbon LCC based Rank							
Retrofit	**Nova Scotia**	**New Brunswick**	**Quebec**	**Ontario**	**Manitoba**	**Saskatchewan**	**Alberta**	**BC**
R1	8	9	8	9	5	10	10	10
R2	4	6	7	7	3	7	9	9
R3	2	2	1	5	2	2	4	3
R4	3	3	10	1	10	3	2	4
R5	7	7	9	4	9	5	3	6
R6	6	4	6	3	8	4	1	1
R7	1	1	2	2	1	1	7	2
R8	10	10	5	10	7	9	8	8
R9	9	8	4	8	6	8	6	7
R10	5	5	3	6	4	6	5	5

Table 7-5 lists energy retrofit investment analysis for eight Canadian provinces, assuming that the building is located in the respective province. The analysis was not conducted for Prince Edward Island, Newfoundland and Labrador, Yukon, and Northwestern Territories due to data unavailability. Results show that geographical variation is a main factor affecting the optimal retrofit. NZEI for different provinces of Canada. NZEI per floor area was calculated in the analysis. This data would assist in capital budget planning for building energy retrofits.

Table 7-5: NZEI for recreational centre buildings

Province		Nova Scotia	New Brunswick	Quebec	Ontario	Manitoba	Saskatchewan	Alberta	BC
Net zero emission Investment (NZEI)	Total	2,902,757	1,887,861	762,719	1,295,502	639,711	1,887,861	2,689,253	924,460
	CAD / m^2	314	204	83	140	69	204	291	100

Figure 7-5 presents NZEI as a function of the provincial grid emission factor. There is a strong correlation (R^2=0.9715) between grid emission factor and NZEI.

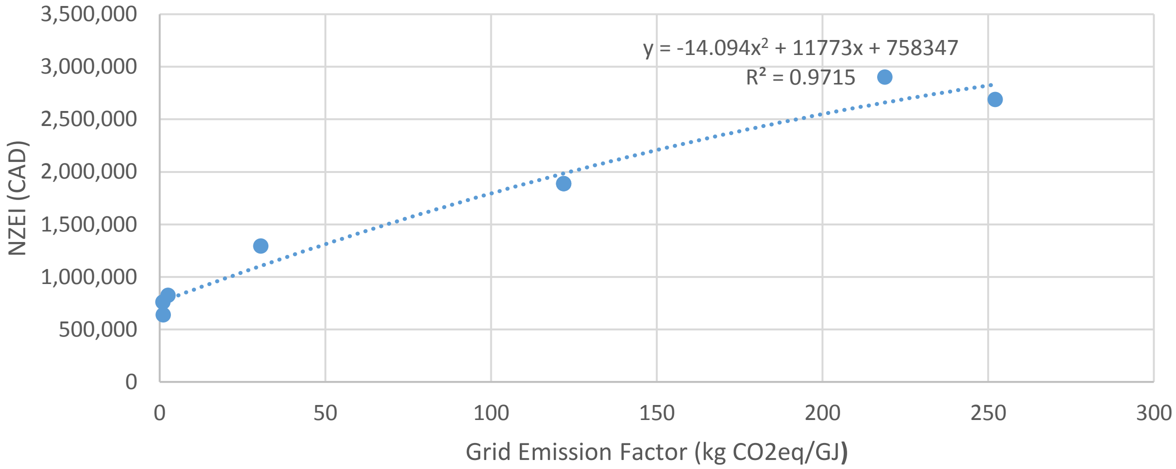


Figure 7-5: NZEI vs grid emission factor

7.4 Discussion

Considering sustainability, renovation, and refurbishments of existing buildings is a more prudent approach compared to new building construction. Building renovation and refurbishment leads to improved functional quality and durability besides being a cost-effective solution compared to demolition and reconstruction (Poel et al. 2007). Moreover, the use of proper refurbishment methods contributes to the development of environmentally sound buildings with an minimized social and financial impacts throughout the life cycle (Poel et al. 2007).

A planned and systematic investment planning approach was proposed for achieving NZEB. An energy simulation analysis was conducted to identify the optimal energy retrofit investment to achieve net-zero emission status. This study was extended to various provinces in Canada to identify the impact of regional grid and energy (i.e. electricity and natural gas) rates on the retrofit investment planning. The proposed approach can be applied in budgeting for building energy retrofits. At the present, retrofits are planned on an ad-hoc basis. The proposed systematic procedure will ensure value for money when operating under limited financial resources. Per floor area investment cost identified from this study can be used directly in energy investment planning for aquatic centre buildings with similar configurations.

Based on the analysis, the economic and environmental viability of a retrofit would change from locational parameters (e.g. energy tariff, grid emission factor). Hence, technology proven to be the most suitable in one province would not be feasible in a different province. Detailed analysis is needed before retrofitting the built environment. This study further investigated the correlation between grid emission factor and NZEI. The strong correlation reveals that larger investments are needed to become net-zero emission in provinces such as Alberta and Nova Scotia.

Retrofits were ranked using multi attribute decision making by assigning equal weights to energy demand reduction, GHG emission reduction and annualized LCC. Therefore, the optimal retrofit changed significantly for different provinces. As an example, for Alberta daylight sensors ranked the highest. Geothermal heating which was ranked 1st and 2nd in many provinces was ranked 7th in Alberta. This difference was due to province's low natural gas tariff (CAD 1.91) and high grid emission factor (910 CO_{2eq}/Kwh).

Several studies in the past have revealed that excluding the end-of-life stage, retrofitted buildings outpace new buildings in assembly and operational phases on environmental performance (McGrath et al. 2013). Building retrofits are commonly analyzed based on the impact on energy and life cycle costs, overlooking other life cycle impacts (Jafari & Valentin 2015). Other factors such as economy and impacts on the ecological environment and heritage value can affect the decision making related to refurbishments (Kovacic et al. 2015). Life cycle impacts differ depending on the geographic location. Hence, incorporating the life cycle impacts of retrofits from a comprehensive LCA can contribute to a holistic analysis of retrofits. These decisions should be supported by adequate information, incentives, knowledge, and access to capital (Hinnells 2008). Currently, the construction industry lacks such decision support frameworks.

In the context of the building considered, net-zero emissions status does not achieve net-zero energy or net-zero cost states. The primary reason is the zero-emission hydroelectricity used in the building. Even though the emission factor of the BC electricity grid is 9.1g $CO_{2\ (eq)}$/kWh, energy utility companies supply electricity with low emission factors. Therefore, net-zero cost status is not achieved during the zero-emission stage. Energy operational cost reduction at NZEI in provinces with high grid emission factor (e.g. Alberta) would be larger compared to low grid emission factor province (e.g. BC). Low emission electricity can be purchased from utility companies at a higher tariff, lowering the initial net-zero emission retrofit investment.

Though buildings are classified net-zero energy or net-zero emissions, these buildings can yet be connected to the grid (Steven Winter Associates Inc. 2014). This energy would be utilized at times when renewable energy cannot cater the building energy demand. Where the law permits, the surplus on-site generation can be supplied to the grid. Due to the high costs associated with energy storage, grid connectivity provides better means of ensuring the reliability of a building energy system. Energy exported from the building to the grid reduces net operational cost of the building. Eventually zero cost status can be achieved by reducing utility bills through lower energy use, and by selling on-site electricity to the grid until the two break even.

Implementing NZEI is a challenge due to budgetary restrictions imposed on public entities. These retrofits should be implemented as annual packages to match the annual budget allocation. Hence, a systematic sequential procedure should be adopted to achieve the eventual zero emission status. Despite the huge interest within the industry on NZEB, limited frameworks are available within the industry to guide the users to achieve zero emission status.

7.5 Summary

This chapter focused on identifying the optimal retrofit investment for commercial and institutional buildings based on energy, carbon emissions, and life cycle cost. The proposed methodology defines a systematic approach for building retrofit planning, which has been performed on an ad hoc basis. The impact of regional variations (geography, tariff structure and policy) on the building retrofits was explored. The optimal retrofit alternative varies in various geographical locations, due to the climate and tariffs. Furthermore, the analysis revealed that NZEI is strongly correlated with the grid emission factor. Findings of this chapter would aid energy engineers and facilities managers in retrofit planning and budget setting.

Chapter 8 Conclusions and Recommendations

Increased awareness of climate change mitigation and declining physical conditions of the existing building stock have called for advanced building management techniques to mitigate the environmental impacts and reduce the rate of deterioration. This research proposed a novel approach for asset management of public buildings. The proposed approach enhances building asset management decision making, by identifying the best intervention strategy that enables GHG emission targets to be achieved at the lowest LCC while also minimizing the risk.

8.1 Summary and Conclusions

A summary of the specific sections of the study and the main conclusions are presented below.

Chapter 4 proposed a LOS assessment approach for building infrastructure, and developed a LOS index for public recreational centre buildings. The proposed framework is an objective method for assessing performance during the operational phase. The proposed LOS based approach addresses a number of shortcomings in current building performance evaluation methods. Additionally, the use of FSE enables the incorporation of vague, incomplete, and qualitative data into the analysis. This approach would assist building managers in monitoring and managing the performance of operating buildings. Further, the proposed approach can be customized to suit the function of the public building. The implementation of this framework was demonstrated for a public aquatic centre building operating Okanagan, BC, Canada. This approach provided three levels of detail for operational management of public buildings, which are strategic, tactical and operational management.

Chapter 5 proposed a fuzzy logic-based LCCA approach for building energy retrofits, which enables the estimation of overall costs of energy retrofit alternatives, and facilitates the selection of the optimal course of action with the lowest overall cost. The proposed approach eliminates several criticisms associated with current LCCA methods. The output membership function depicts the possible range of LCC associated with the retrofit. Even though the deterministic result has a high membership to the fuzzy membership function, the possible LCC spans a wide range. Moreover, the fuzzy-based result encompasses detailed information on the possible LCC, which enables planning for possible adverse scenarios in the future.

Chapter 6 proposed a multi-period maintenance planning approach for public buildings. This approach incorporates a scenario-based approach for deciding the best capital planning strategy based on value at risk. Risk based prioritization is used to select the critical building systems / components. Fuzzy logic was used to incorporate the uncertainties associated with building condition, costs, and retrofit impacts. The proposed method would support capital asset planning of local governments by identifying the best maintenance strategy.

Chapter 7 proposed a systematic approach for building retrofit investment planning, which has so far been performed on an ad hoc basis in practice. This study explored the impact of regional variations on the building retrofits. Furthermore, the findings of this research revealed that NZEI is strongly correlated to the grid emission factor. Findings of this study aid retrofit planning and budget setting.

Figure 8-1 depicts where the aforementioned methods would fit into the strategy map. Proposed methods would mainly support building owners and managers in achieving climate action targets of the institution while maintaining the condition rating of the building. Having such standardized procedures for implementation would reinforce climate-driven asset management function.

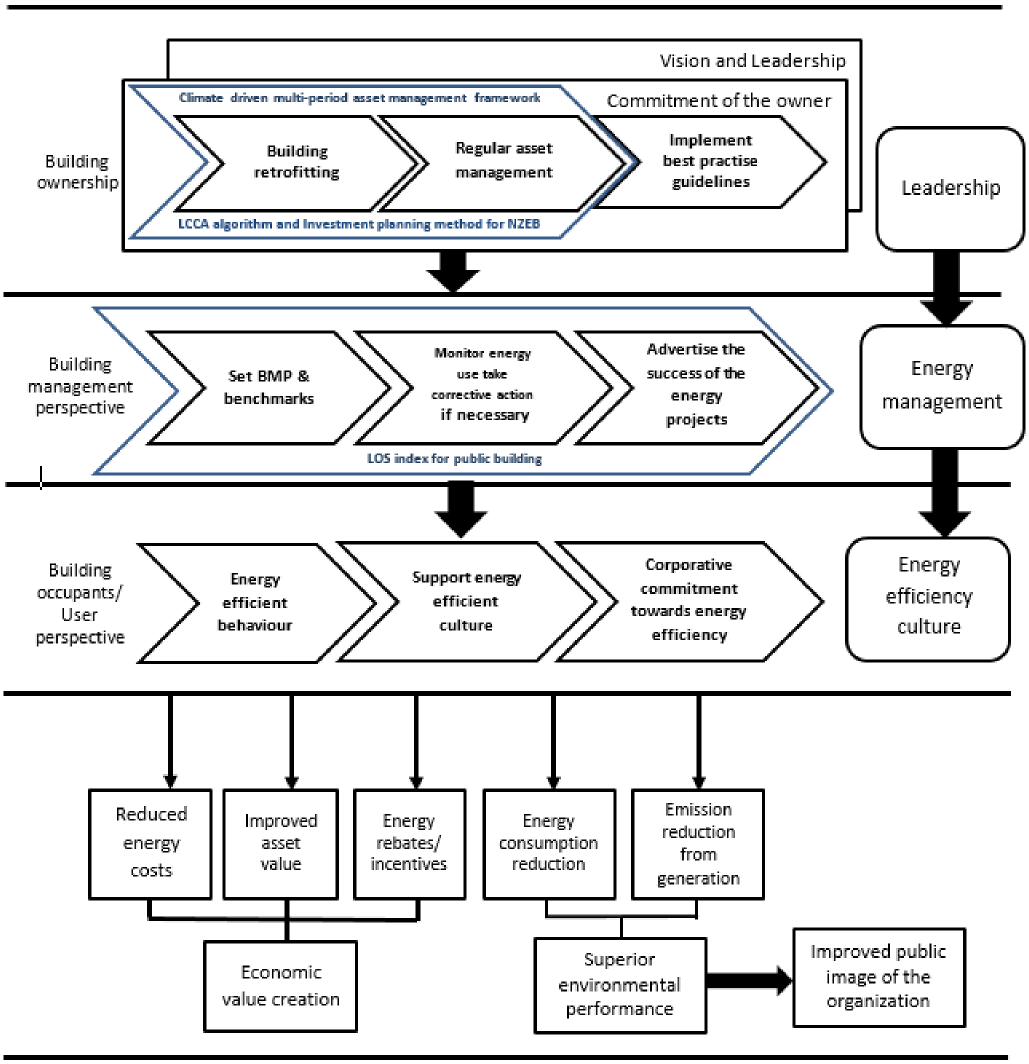


Figure 8-1: Implementation of the deliverables

8.2 Originality and Contributions

This research is expected to deliver two unique contributions which would assist improving the performance of public buildings through an asset management lens.

Enhancing the strategic asset management decision making: This research developed a life cycle thinking based asset management framework for public buildings. The proposed framework addresses the deficiencies associated with current asset management methods by integrating risk management, multi-period planning, uncertainty assessment, maintenance planning, and spatial variation to develop an innovative methodology. Previous asset management approaches ignore the interaction between macro-economic factors, future technology advancements, and cost changes. Building maintenance planning approach proposed in this study addresses the aforementioned limitations in the current methods. Furthermore, a risk based approach (VaR) is used to compare alternative strategies for long-term planning.

Redefining operational management of public buildings: This study proposes a LOS index for public buildings. There is a large number of building rating systems available in the literature. However, practical value of implementing these rating systems is a grey area. The majority of these rating systems are biased towards a research focus, and are not ideal for practical implementation. As a result, these rating systems become redundant primarily due to their practical inflexibility. LOS has been used in infrastructure management, and can be adopted for municipal buildings to monitor and manage building performance. The comprehensive literature review could not find any previous studies that have calculated the LOS of a public building.

8.3 Limitations of the Study

Limitations identified in this study are discussed below. Adjustments were made to mitigate their impacts.

Focus on the operational stage of the building: This research only focused on the operational stage of the building and building components that mainly affect the energy consumption. Structural performance of the building was considered to be beyond the scope of this study. The contributions from this research are internal building management methods developed for public sector buildings. Public sector is service oriented rather than profit oriented. This approach could be used in a different context (private users) by adjusting benchmarks and category weights. The flexibility is provided to the users to customize this approach to suit their needs. Base line performance is specified using literature as the foundation.

This study used a standard aquatic centre building to demonstrate this study. The sample building was used to calculate NZEI and ranking of retrofits. NZEI for Canadian provinces could be generalized only after extensive studies. The above results could be used for buildings with similar configurations, even though NZEI could differ due to other factors such as the building use, size etc.

Monetary focus: This research does not consider non-monetary costs or benefits of building energy retrofits. Examples of non-monetary benefits and costs include an HVAC system with less noise, improved efficiency from a new lighting system with a better illumination level, health impacts from a renewable energy, and energy independence due to the use of a geothermal heating system. These factors should be considered in an investment decision, extending the decision making process beyond the economic aspect. However, LOS approach assesses the building performance related to qualitative performance.

Moreover, the proposed approach does not account for external costs and benefits (e.g. environmental benefits and social impacts) or an increase in the market value of the building due to higher energy performance. The results of this approach focus purely on the economic perspective. Accounting for external benefits may make marginal retrofits more attractive. A multi-criteria decision analysis can identify the optimal retrofit based on organizational priorities.

Data limitations: Specific data collection had been a challenge in this study. Information such as component performance data was not available due to a number of reasons, such as the unavailability of sub-metering and the extensive time required for a condition survey. Weight schemes were used in multiple instances (e.g. LOS index). Assumptions supported by published literature were used wherever necessary. Since the focus of this research was to propose the method, literature based data provided an acceptable level of accuracy.

There is significant uncertainty associated with the data used in this study. Fuzzy logic was used to account for data uncertainty. This research mainly assumed trapezoidal and triangular fuzzy numbers for uncertain data. Even though representing data using fuzzy numbers is the more reliable method (as opposed to crisp values), there is still a degree of uncertainty associated with it. This uncertainty could be minimized by using more reliable data and consulting experts with substantial experience. The above aspects were considered to be beyond the scope of this research.

Scenario uncertainty is a major limitation associated with this approach. Scenario development methods specified in the literature was used to define the scenarios used in this study. Furthermore, expert opinion was sought to assess the plausibility of scenarios.

Utility rates are subject to the inflation prevailing at that time. Moreover, there can be rate arrangements between building owners and utility providers. This drawback was minimized by adopting novel energy retrofit life cycle costing methods. This approach ignored the time dependency of grid source energy. Time dependent valuations for time of use source energy is an important factor in determining the net-zero emissions. Hence, real-time building management is needed to maintain the net-zero emission status.

Limitations in energy simulations: Thermal processes within a building are complex and difficult to understand , which makes manual calculations difficult (Maile et al. 2007). As a remedy, energy simulation programs approximate their predictions with qualified equations and methods. An energy simulation software incorporates energy principles, thermodynamic equations, and many assumptions. The accuracy of the building energy simulation results depends in turn on the accuracy of input data for the simulation (Maile et al. 2007). Input data for the building energy model includes building geometry, internal loads, HVAC systems and components, weather data, operating strategies and schedules, as well as simulation specific parameters. If certain assumptions are not satisfied in the simulation or data is not matched in real life, the simulation results could turn out to be incorrect.

8.4 Future Research

Following research area were identified as potential extensions of this research.

Implementation and integration: This research is aimed at improving the operational performance of public buildings by mobilizing tactical and operational management with easy-to-use resources based on scientific backing. Further research is needed on implementing the findings from this research. Characteristics such as life cycle impacts, service life vary from one retrofit to another. Hence, further research is required to assess the industry requirements and challenges for implementing similar approaches in the industrial context. It is important to focus on developing an integrated building asset management tool to be implemented in municipalities. The unique features of this tool include individual and portfolio management, users' ability to alter benchmarks and weights based on their priorities, and the ability to incorporate vague and imprecise data. Currently, user friendly tools are being developed for the partner municipality to implement the outcomes of this research.

Impact of climate change: The increase in atmospheric temperature due to global warming has adversely affected energy performance, indoor air quality, thermal comfort, and sustainability of commercial buildings. The current and future buildings should be capable of adapting to the changes in local climatic conditions throughout the building's service life. It is predicted that more cooling and less heating will be required in the future. As an example, a study in Australia identified that from 2020-2080 the building energy consumption would change from -0.6% and 8.3%, and the cooling equipment capacity should be increased by 9.1% to 25% due to climate change. Hence, more accurate weather data considering future patterns can be an important determinant in future building designs. Future research should focus on aforementioned focus areas.

Research on behavioural aspects: Limited studies have focused on the rebound effect of energy consumption due to a reduction in energy cost. An increase in energy demand could trade off the benefits of energy cost reduction. Therefore, it is vital to look at the potential of human actions to improve or diminish the energy efficiency of commercial buildings. Further research should focus on examining, experimenting, and optimizing different energy management strategies and occupancy interventions for commercial and institutional buildings.

References

AASHTO, 2011. *AASHTO Transportation Asset Management Guide: A Focus on Implementation*, Washington, DC: American Association of State Highway and Transportation Officials.

AbouRizk, S., Siu, K.L. & Allouche, M., 2005. Edmonton's Risk Analysis Approach to the Infrastructure Gap. Available at: http://www.edmonton.ca/city_government/documents/PDF/Summit_Article_-_Jan-Feb_2005.pdf [Accessed May 25, 2015].

Agarwal, P. & Nayal, H.S., 2015. Possibility Theory versus Probability Theory in Fuzzy Measure Theory. *Int. Journal of Engineering Research and Applications*, 5(5), pp.37–43.

Ahmad, Z. et al., 2009. Assessment of Property Management Service Quality of Purpose Built Office Buildings Assessment of Property Management Service Quality of Purpose Built Office Buildings. *International Business Research*, 2(1), pp.162–174.

Airaksinen, M. & Matilainen, P., 2011. A Carbon Footprint of an Office Building. *Energies*, 4(12), pp.1197–1210. Available at: http://www.mdpi.com/1996-1073/4/8/1197/ [Accessed May 15, 2014].

Alexandre, J.L. et al., 2011. Impact of European standard EN15251 in the energy certification of services buildings—A Portuguese study case. *Energy Policy*, 39(10), pp.6390–6399. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421511005714 [Accessed August 27, 2014].

Altwies, J.E. & Nemet, G.F., 2013. Innovation in the U.S. building sector: An assessment of patent citations in building energy control technology. *Energy Policy*, 52, pp.819–831. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421512009354 [Accessed October 14, 2014].

Ammar, M., Zayed, T. & Moselhi, O., 2013. Fuzzy-Based Life-Cycle Cost Model for Decision Making under Subjectivity. *Journal of Construction Engineering and Management*, 139(5), pp.51–60.

Andrews, C.J. & Krogmann, U., 2009. Explaining the adoption of energy-efficient technologies in U.S. commercial buildings. *Energy and Buildings*, 41(3), pp.287–294. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778808002156 [Accessed May 11, 2014].

Artmann, N., Manz, H. & Heiselberg, P., 2008. Parameter study on performance of building cooling by night-time ventilation. *Renewable Energy*, 33(12), pp.2589–2598. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0960148108000748 [Accessed October 10, 2014].

Asadi, E. et al., 2012. A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB. *Building and Environment*, 56, pp.370–378. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132312001217.

Asadi, E. et al., 2014a. Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application. *Energy and Buildings*, 81, pp.444–456. Available at: http://dx.doi.org/10.1016/j.enbuild.2014.06.009.

Asadi, E. et al., 2014b. Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application. *Energy and Buildings*, 81, pp.444–456.

Ashrafian, T. et al., 2016. Methodology to define cost-optimal level of architectural measures for energy efficient retrofits of existing detached residential buildings in Turkey. *Energy and Buildings*, 120, pp.58–77. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778816302304.

Assaf, S.A. et al., 2002. Assessment of the problems of application of life cycle costing in construction projects. *Cost Engineering*, 44(2), pp.17–22.

Asset Management BC, 2011. *Guide for using the Asset Management BC Roadmap*, British Columbia.

ATCO Gas, 2016. Current Rate Summary. Available at: http://www.atcogas.com/Rates/Current_Rates/Current-Rates-South-Customer-Rate-Summary [Accessed July 14, 2016].

Augenbroe, G., Castro, D. & Ramkrishnan, K., 2009. Decision model for energy performance improvements in existing buildings. *Journal of Engineering, Design and Technology*, 7(1), pp.21–36. Available at: http://dx.doi.org/10.1108/17260530910947240.

Azar, E. & Menassa, C.C., 2014. A comprehensive framework to quantify energy savings potential from improved operations of commercial building stocks. *Energy Policy*, 67, pp.459–472. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421513012755 [Accessed September 22, 2014].

Bank of Canada, 2016. Inflation. Available at: http://www.bankofcanada.ca/core-functions/monetary-policy/inflation/ [Accessed March 28, 2016].

Bansal, N.K. & Goel, S., 2000. Integration of photovoltaic technology in cafeteria building , at Indian Institute of Technology , New Delhi. *Renewable Energy*, 19(2000), pp.65–70.

Batista, N.D.N., Rovere, E.L. La & Aguiar, J.C.R., 2011. Energy efficiency labeling of buildings: An assessment of the Brazilian case. *Energy and Buildings*, 43(6), pp.1179–1188. Available at: http://linkinghub.elsevier.com/retrieve/pii/S037877881000407X [Accessed August 8, 2014].

BC Ministry of Health, 2014. *B.C. Guidelines for pool design*, Victoria, BC. Available at: http://www2.gov.bc.ca/assets/gov/environment/air-land-water/pool_design_guidelines_jan_2014_final.pdf.

Berardi, U., 2012. Sustainability Assessment in the Construction Sector: Rating Systems and Rated Buildings. *Sustainable Development*, 20(6), pp.411–424. Available at: http://doi.wiley.com/10.1002/sd.532.

Bhandari, M., Shrestha, S. & New, J., 2012. Evaluation of weather datasets for building energy simulation. *Energy and Buildings*, 49, pp.109–118. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778812000503 [Accessed August 21, 2014].

Borgstein, E.H. & Lamberts, R., 2014. Developing energy consumption benchmarks for buildings: Bank branches in Brazil. *Energy and Buildings*, 82, pp.82–91. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778814005659 [Accessed September 1, 2014].

Borreguero, A.M. et al., 2014. Polymeric-SiO2-PCMs for improving the thermal properties of gypsum applied in energy efficient buildings. *Energy Conversion and Management*, 87, pp.138–144. Available at: http://linkinghub.elsevier.com/retrieve/pii/S019689041400658X [Accessed September 2, 2014].

BRE Global, 2012. *Briefing Paper. BREEAM In-Use. Driving sustainability through existing buildings*, Watford, UK. Available at: http://www.breeam.org/filelibrary/BREEAM In Use/KN5686---BREEAM-In-Use-White-Paper_dft2.pdf.

BRE Global, 2015. Post-Occupancy Evaluation (POE). Available at: https://www.bre.co.uk/page.jsp?id=1793 [Accessed January 11, 2016].

Brown, R., Webber, C. & Koomey, J.G., 2002. Status and future directions of the Energy Star program. *Energy*, 27(5), pp.505–520. Available at: http://linkinghub.elsevier.com/retrieve/pii/S036054420200004X.

Bruno, F., 2011. On-site experimental testing of a novel dew point evaporative cooler. *Energy and Buildings*, 43(12), pp.3475–3483. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778811004014 [Accessed November 18, 2014].

Buck, J. & Young, D., 2007. The potential for energy efficiency gains in the Canadian commercial building sector: A stochastic frontier study. *Energy*, 32(9), pp.1769–1780. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360544206003306 [Accessed August 27, 2014].

Bull, J.W., 1993. *Life cycle costing for construction*, London, UK: Spon press.

Bynum, J.D., Claridge, D.E. & Curtin, J.M., 2012. Development and testing of an Automated Building Commissioning Analysis Tool (ABCAT). *Energy and Buildings*, 55, pp.607–617. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778812004422 [Accessed October 6, 2014].

Canada`s Action on Climate Change, 2013. Copenhagen Accord. Available at: http://climatechange.gc.ca/default.asp?lang=En&n=AA3F6868-1.

Canada Green Building Council, 2009a. *LEED® Canada for Existing Buildings: Operations and Maintenance 2009*, Ottawa, ON.

Canada Green Building Council, 2009b. *LEED® Canada for Existing Buildings: Operations and Maintenance 2009*, Ottawa, ON. Available at: http://www.cagbc.org/AM/PDF/LEED Canada EBO&M rating system.pdf.

Canadian Centre for Occupational Health & Safety, 2017. Emergency Planning. Available at: https://www.ccohs.ca/oshanswers/hsprograms/planning.html [Accessed January 21, 2017].

Canadian Construction Association, 2012. *Guide to Cost Predictability in Construction : An Analysis of Issues Affecting the Accuracy of Construction Cost Estimates*, Ottawa, ON. Available at: http://www.cca-acc.com/pdfs/en/CCA/Guide_to_Cost_Predictability.pdf.

Canadian Infrastructure Report Card, 2016. *Canadian Infrastructure Report Card: Informing the Future*, Available at: www.canadainfrastructure.ca/downloads/Canadian_Infrastructure_Report_2016.pdf.

Cao, Y., Wang, T. & Song, X., 2015. Automation in Construction An energy-aware , agent-based maintenance-scheduling framework to improve occupant satisfaction. *Automation in Construction*, 60, pp.49–57. Available at: http://dx.doi.org/10.1016/j.autcon.2015.09.002.

Carlo, J. & Lamberts, R., 2008. Development of envelope efficiency labels for commercial buildings: Effect of different variables on electricity consumption. *Energy and Buildings*, 40(11), pp.2002–2008. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778808001114 [Accessed July 31, 2014].

Cavique, M. & Gonçalves-Coelho, a. M., 2009. Axiomatic design and HVAC systems: An efficient design decision-making criterion. *Energy and Buildings*, 41(2), pp.146–153. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778808001813 [Accessed November 18, 2014].

CEI Architecture Planning Interiors, 2011. *UBC New Aquatic Centre Study*, Vancouver, BC.

Center for the Built Environment (CBE), 2013. About Mixed-Mode. Available at: http://www.cbe.berkeley.edu/mixedmode/aboutmm.html [Accessed May 23, 2015].

Chae, Y.T. et al., 2014. Building energy performance evaluation of building integrated photovoltaic (BIPV) window with semi-transparent solar cells. *Applied Energy*, 129, pp.217–227. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261914004693 [Accessed September 21, 2014].

Chang, H., Kato, S. & Chikamoto, T., 2004. Effects of outdoor air conditions on hybrid air conditioning based on task/ambient strategy with natural and mechanical ventilation in office buildings. *Building and Environment*, 39, pp.153–164.

Chang, Q. et al., 2015. MSPA-Based Urban Green Infrastructure Planning and Management Approach for Urban Sustainability: Case Study of Longgang in China. *Journal of Urban Planning & Development*, 141(3), pp.1–15. Available at: http://10.0.4.37/(ASCE)UP.1943-5444.0000247%5Cnhttp://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=109020271&site=ehost-live.

Chasey, A.D., Garza, J.M.D. La & Drew, D.R., 1997. Comprehensive Level of Service: Needed Approach for Civil Infrastructure Systems. *Journal of Infrastructure Systems*, 3(4), pp.143–153.

Chiang, Y., Zhou, L. & Li, J., 2014. Achieving Sustainable Building Maintenance through Optimizing Life-Cycle Carbon, Cost, and Labor: Case in Hong Kong. *Journal of Construction …*, 140(3), pp.1–10. Available at:

http://ascelibrary.org/doi/abs/10.1061/(ASCE)CO.1943-7862.0000823.

Chidiac, S.E. et al., 2011. A screening methodology for implementing cost effective energy retrofit measures in Canadian office buildings. *Energy and Buildings*, 43(2–3), pp.614–620.

Choudhry, M., 2013. *An Introduction to Value-at-Risk, Fifth Edition* 5th ed., West Sussex: Wiley.

Chow, S.K.H. et al., 2013. Analysis and prediction of daylighting and energy performance in atrium spaces using daylight-linked lighting controls. *Applied Energy*, 112, pp.1016–1024. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261912009154 [Accessed August 22, 2014].

Chow, T.-T., Li, C. & Lin, Z., 2011. The function of solar absorbing window as water-heating device. *Building and Environment*, 46(4), pp.955–960. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132310003197 [Accessed October 3, 2014].

Chua, K.J. et al., 2013. Achieving better energy-efficient air conditioning – A review of technologies and strategies. *Applied Energy*, 104, pp.87–104. Available at: http://linkinghub.elsevier.com/retrieve/pii/S030626191200743X [Accessed July 14, 2014].

Chua, K.J. & Chou, S.K., 2010. An ETTV-based approach to improving the energy performance of commercial buildings. *Energy and Buildings*, 42(4), pp.491–499. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778809002564 [Accessed August 7, 2014].

Chung, W., 2012. Using the fuzzy linear regression method to benchmark the energy efficiency of commercial buildings. *Applied Energy*, 95, pp.45–49. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261912000670 [Accessed July 14, 2014].

Chung, W., Hui, Y.V. & Lam, Y.M., 2006. Benchmarking the energy efficiency of commercial buildings. *Applied Energy*, 83(1), pp.1–14. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261904002028 [Accessed August 4, 2014].

CIBSE, 2001. *Energy use in sports and recreation buildings*, Watford. Available at: http://www.cibse.org/getmedia/34def23a-c65b-405e-9dff-ce181c0b1e0d/ECG78-Energy-Use-in-Sports-and-Recreation-Buildings.pdf.aspx.

City of Nelson, 2013. *Bicycle Parking Design Guidelines*, Nelson, BC. Available at: http://www.nelson.ca/assets/City~Services/Pubs~and~Reports/Development~Services/Bicy cle Parking Design Guidelines.pdf.

City of Timmins, 2016. *Aquatic Centre Feasibility Study*, Timmins. Available at: http://www.timmins.ca/220/uploads/Timmins_Aquatic_Centre_Feasibility_Study_-_July_2016_Final_ReportV2-jb0b3.pdf.

City of Toronto, 2009. Community Centre and Pools : Energy Retrofit Case Study. Available at: https://www1.toronto.ca/City Of Toronto/Environment and Energy/Key Priorities/Files/pdf/R/Retrofit/community_centre_case_study.pdf [Accessed June 8, 2016].

City of Toronto, 2014. *Energy Conservation and Demand Management (ECDM) Plan*, Toronto, ON.

Coghlan, D. & Brydon-Miller, M., 2014. Fishbone Diagram. *The SAGE Encyclopedia of Action Research*. Available at: http://dx.doi.org.ezproxy.library.ubc.ca/10.4135/9781446294406.

Condominium home owners association, 2012. What happens over the life of a building? Available at: http://www.choa.bc.ca/_resources/Bulletin04_Life_of_Buildings.pdf [Accessed May 24, 2015].

Correia, A.R. & Wirasinghe, S.C., 2008. Analysis of level of service at airport departure lounges: user perception approach. *Journal of Transportation Engineering*, 134(2), pp.105–109.

Creese, R.C. & Moore, L.T., 1990. Cost Modeling for Concurrent Engineering. *Cost Engineering*, 32(6), p.23.

Curtis, J., Walton, A. & Dodd, M., 2017. Understanding the potential of facilities managers to be advocates for energy efficiency retrofits in mid-tier commercial office buildings. , 103(January), pp.98–104.

Daly, D., Cooper, P. & Ma, Z., 2014. Implications of global warming for commercial building retrofitting in Australian cities. *Building and Environment*, 74, pp.86–95. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132314000110 [Accessed September 4, 2014].

Dasgupta, S. & Tam, E.K.., 2005. Indicators and framework for assessing sustainable infrastructure. *Canadian Journal of Civil Engineering*, 32, pp.30–44.

Dempster, M.A.H., 2002. *Risk Management: Value at Risk and Beyond*, Cambridge, UK: Cambridge University Press.

Dhillon, B.S., 2010. *Life cycle costing for engineers*, Boca Raton, FL: Taylor & Francis.

Du, Z. et al., 2014. Fault detection and diagnosis for buildings and HVAC systems using combined neural networks and subtractive clustering analysis. *Building and Environment*, 73, pp.1–11. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132313003417 [Accessed October 15, 2014].

Edirisinghe, R., Setunge, S. & Zhang, G., 2015. Markov Model — Based Building Deterioration Prediction and ISO Factor Analysis for Building Management. *Journal of Management in Engineering*, pp.1–9.

Ehrlich, C. et al., 2002. A method for simulating the performance of photosensor-based lighting controls. *Energy and Buildings*, 34(9), pp.883–889. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778802000646.

Eicker, U. et al., 2008. Fa??ades and summer performance of buildings. *Energy and Buildings*, 40, pp.600–611.

El-rayes, K. et al., 2016. Discrete Markov Approach for Building Component Condition, Reliability, and Service-Life Prediction Modeling. *J. Perform. Constr. Facil.*, 30(5), pp.1–9.

Energy star, 2015. Buildings & Plants. Available at: https://www.energystar.gov/buildings?s=mega [Accessed November 23, 2015].

Enridge Gas New Brunswick, 2016. *Handbook of Rates and Distribution Services*, Fredericton, NB.

Ens, A., 2012. *Development of a Flexible Framework for Deterioration Modelling in Infrastructure Asset Management*. University of Toronto.

Environment Canada, 2014a. *National Inventory Report 1990-2012*, Ottawa, ON. Available at: http://publications.gc.ca/collections/collection_2014/ec/En81-4-2012-3-eng.pdf.

Environment Canada, 2014b. *National Inventory Report 1990–2012*, Gatineau, QC. Available at: http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=3808457C-1&offset=6&toc=show.

Environment Canada, 2013. Planning for a Sustainable Future: A Federal Sustainable Development Strategy for Canada 2013–2016. Available at: https://www.ec.gc.ca/dd-sd/default.asp?lang=en&n=B8F4119E-1#fnb6.

Escrivá-Escrivá, G., 2011. Basic actions to improve energy efficiency in commercial buildings in operation. *Energy and Buildings*, 43(11), pp.3106–3111. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778811003409 [Accessed January 13, 2014].

Escrivá-Escrivá, G., Santamaria-Orts, O. & Mugarra-Llopis, F., 2012. Continuous assessment of energy efficiency in commercial buildings using energy rating factors. *Energy and Buildings*, 49, pp.78–84. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778812000357 [Accessed March 28, 2014].

Estes, H.M., 2011. *Economic Analysis of Energy Retrofit*. University of Alabama.

Ettouney, M.M. & Alampalli, S., 2012. *Infrastructure Health in Civil Engineering: Applications and Management*, Boca Raton, FL: CRC Press.

European Commission, 2012. *Health Effects of Artificial Light*, Brussels: European Union. Available at: http://ec.europa.eu/health/scientific_committees/opinions_layman/artificial-light/en/index.htm [Accessed May 12, 2015].

Ezzeldin, S. & Rees, S.J., 2013. The potential for office buildings with mixed-mode ventilation and low energy cooling systems in arid climates. *Energy and Buildings*, 65, pp.368–381. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.06.004.

Fan, Y. & Xia, X., 2017a. A multi-objective optimization model for energy-efficiency building envelope retrofitting plan with rooftop PV system installation and maintenance. *Applied Energy*, 189, pp.327–335. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261916318505.

Fan, Y. & Xia, X., 2017b. A multi-objective optimization model for energy-efficiency building envelope retrofitting plan with rooftop PV system installation and maintenance. *Applied Energy*, 189, pp.327–335.

Fan, Y. & Xia, X., 2016. An optimal maintenance plan for building envelope insulation materials after retrofitting. *Proceedings - 2015 Chinese Automation Congress, CAC 2015*, pp.2068–2073.

Fasiuddin, M. & Budaiwi, I., 2011. HVAC system strategies for energy conservation in commercial buildings in Saudi Arabia. *Energy and Buildings*, 43(12), pp.3457–3466. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778811003926 [Accessed July 24, 2014].

Federation of Canadian Municipalities, 2011. *Building Canadas Green Economy : The Municipal Role*, Ottawa, ON.

Federation of Canadian Municipalities, 2003. *Developing indicators and bechmarks*, Ottawa, ON.

Federation of Canadian Municipalities, 2002. *Developing Levels of Service*, Ottawa, ON.

Félio, G.Y. & Lounis, Z., 2009. *Model Framework for Assessment of State, Performance, and Management of Canada's Core Public Infrastructure*, Ottawa, ON. Available at: http://www.nrtsi.ca/documents/Framework.E.pdf.

Ferrara, M. et al., 2014. A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings. *Energy and Buildings*, 84, pp.442–457. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778814006732.

Fong, K.F., Hanby, V.I. & Chow, T.T., 2006. HVAC system optimization for energy management by evolutionary programming. *Energy and Buildings*, 38(3), pp.220–231. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778805000939 [Accessed September 27, 2014].

Fontanini, A., Vaidya, U. & Ganapathysubramanian, B., 2013. A stochastic approach to modeling the dynamics of natural ventilation systems. *Energy and Buildings*, 63, pp.87–97. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813002223 [Accessed November 19, 2014].

FortisBC, 2016. Rate Schedule.

Foster, R., Ghassemi, M. & Cota, A., 2010. *Solar Energy: Renewable Energy and the Environment*, Boca Raton, FL: Taylor & Francis.

Frappé-Sénéclauze, T.-P. & Kniewasser, M., 2015. *The Path to "Net-Zero Energy" Buildings in BC*, Victoria, BC.

Fuller, S., 2010. Life-Cycle Cost Analysis (LCCA). Available at: https://www.wbdg.org/resources/lcca.php [Accessed January 2, 2016].

Gagliano, a. et al., 2012. Thermal performance of ventilated roofs during summer period. *Energy and Buildings*, 49, pp.611–618. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778812001557 [Accessed November 18, 2014].

Gaz Métro, 2016. Price of natural gas. Available at: http://www.gazmetro.com/en/business/price/natural-gas-price/ [Accessed July 14, 2016].

Government of British Columbia, 2013a. Carbon Neutral Action Reports. Available at: http://www2.gov.bc.ca/gov/topic.page?id=BE9BE637F7BA4FFB97AFFE62181F9A67

[Accessed March 5, 2015].

Government of British Columbia, 2013b. *Carbon Neutral Government Overview*, Victoria, BC.

Government of British Columbia, 2016. Reducing Greenhouse Gas Emissions. Available at: http://www2.gov.bc.ca/gov/content/environment/climate-change/policy-legislation-programs/carbon-neutral-government/reduce [Accessed March 5, 2017].

Goyal, S., Ingley, H. a. & Barooah, P., 2013. Occupancy-based zone-climate control for energy-efficient buildings: Complexity vs. performance. *Applied Energy*, 106, pp.209–221. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261913000482 [Accessed September 5, 2014].

Gransberg, D.D., 2015. *Major Equipment Life-cycle Cost Analysis*, Ames, Iowa.

Green Building Council Denmark, *An introduction to DGNB*,

Green Building Council of Australia, 2015. List of Credits.

Green Building Initiative, 2014. Green Globes for Existing Buildings Blank Survey.

Grussing, M.N., 2009a. Building Envelope Life Cycle Condition Evaluation Using a Distress-Based Methodology. In *International Conference on Applications of Advanced Technology in Trans*. ASCE. Available at: file:///C:/Users/rruparat/Downloads/ASCE Building Envelope Life Condition Evaluation.pdf.

Grussing, M.N., 2009b. Building Envelope Life Cycle Condition Evaluation Using a Distress-Based Methodology. In *International Conference on Applications of Advanced Technology in Trans*. ASCE.

Grussing, M.N., 2013. Life Cycle Asset Management Methodologies for Buildings. *Journal of Infrastructure Systems*, (Fhwa 1999), p.130404171828002. Available at: http://ascelibrary.org/doi/abs/10.1061/(ASCE)IS.1943-555X.0000157.

Grussing, M.N., 2015. *Risk-based facility management approach for building components using a discrete Markov process – Predicting condition, reliability, and remaining service life*. University of Illinois at Urbana-Champaign.

Gvozdenac, D. et al., 2009. Assessment of potential for natural gas-based cogeneration in Thailand. *Energy*, 34(4), pp.465–475. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360544208003289 [Accessed October 3, 2014].

Halfawy, M.M.R., Newton, L.A. & Vanier, D.J., 2006. Review of commercial municipal infrastructure asset management systems. *Electronic Journal of Information Technology in Construction*, 11(May 2005), pp.211–224.

Halfawy, M.R., Dridi, L. & Baker, S., 2008. Integrated Decision Support System for Optimal Renewal Planning of Sewer Networks. *Journal of Computing in Civil Engineering*, 22(6), pp.360–372.

Hall, S., 2014. Development and initial trial of a tool to enable improved energy & human performance in existing commercial buildings. *Renewable Energy*, 67, pp.109–118. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0960148113006009 [Accessed August 27, 2014].

Han, S. et al., 2015. Evaluation of Customer-Driven Level of Service for Water Infrastructure Asset Management. *Journal of Management in Engineering*, 31(4).

Haq, M.A.U. et al., 2014. A review on lighting control technologies in commercial buildings, their performance and affecting factors. *Renewable and Sustainable Energy Reviews*, 33, pp.268–279. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032114001166 [Accessed August 26, 2014].

Harder, J., 2015. The Future of Energy Efficiency. Available at: http://plus.usgbc.org/the-future-of-energy-efficiency/ [Accessed March 4, 2017].

Hartkopf, V. & Loftness, V., 1999. Global relevance of total building performance. *Automation in construction*, 8(4), pp.377–393.

Harvard Health Letter, 2014. Blue light has a dark side. Available at: http://www.health.harvard.edu/staying-healthy/blue-light-has-a-dark-side [Accessed May 12, 2015].

Heravi, G. & Esmaeeli Asghar Nezhadpour, 2014. Fuzzy Multicriteria Decision-Making Approach for Pavement Project Evaluation Using Life-Cycle Cost / Performance Analysis. *Journal of Infrastructure Systems*, 20(2010), pp.1–7.

Heritage Gas, 2016. Rates for Business. Available at: http://www.heritagegas.com/business/rates-business/ [Accessed July 14, 2016].

Hertzsch, E., Heywood, C. & Piechowski, M., 2012. A methodology for evaluating energy efficient office refurbishments as life cycle investments. *International Journal of Energy Sector Management*, 6(2), pp.189–212. Available at:

http://www.emeraldinsight.com/10.1108/17506221211242068 [Accessed May 21, 2014].

Hinnells, M., 2008. Technologies to achieve demand reduction and microgeneration in buildings. *Energy Policy*, 36(12), pp.4427–4433. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421508004618 [Accessed August 25, 2014].

HKGBC, 2010. *BEAM Plus for Existing Buildings*, Hong Kong.

Hossaini, N. et al., 2014. AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame buildings in Vancouver. *Journal of Environmental Planning and Management*, (October 2014), pp.1–25. Available at: http://www.tandfonline.com/doi/abs/10.1080/09640568.2014.920704 [Accessed October 6, 2014].

Hsieh, C.-M., Aramaki, T. & Hanaki, K., 2007. Estimation of heat rejection based on the air conditioner use time and its mitigation from buildings in Taipei City. *Building and Environment*, 42(9), pp.3125–3137. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132306002149 [Accessed November 11, 2014].

Huang, Y. et al., 2011. Biomass fuelled trigeneration system in selected buildings. *Energy Conversion and Management*, 52(6), pp.2448–2454. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0196890411000574 [Accessed September 30, 2014].

Huang, Y. et al., 2013. Comparative techno-economic analysis of biomass fuelled combined heat and power for commercial buildings. *Applied Energy*, 112, pp.518–525. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261913002742 [Accessed September 28, 2014].

Huang, Y.-C. et al., 2013. Building users' perceptions of importance of indoor environmental quality in long-term care facilities. *Building and Environment,* 67, pp.224–230. Available at: http://www.sciencedirect.com/science/article/pii/S036013231300142X.

Huang, Y., Niu, J. & Chung, T., 2013. Study on performance of energy-efficient retrofitting measures on commercial building external walls in cooling-dominant cities. *Applied Energy*, 103, pp.97–108. Available at:

http://linkinghub.elsevier.com/retrieve/pii/S0306261912006435 [Accessed August 6, 2014].

Hussain, F. et al., 2013. Design development and performance evaluation of photovoltaic/thermal (PV/T) air base solar collector. *Renewable and Sustainable Energy Reviews*, 25, pp.431–441. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032113002657 [Accessed August 26, 2014].

Ibn-Mohammed, T. et al., 2014. Integrating economic considerations with operational and embodied emissions into a decision support system for the optimal ranking of building retrofit options. *Building and Environment*, 72, pp.82–101. Available at: http://dx.doi.org/10.1016/j.buildenv.2013.10.018.

Ibrahim, A. et al., 2014. Efficiencies and improvement potential of building integrated photovoltaic thermal (BIPVT) system. *Energy Conversion and Management*, 77, pp.527–534. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0196890413006687 [Accessed August 19, 2014].

Industry Canada, 2013. Buildings. *Corporate Social Responsibility*. Available at: http://www.ic.gc.ca/eic/site/csr-rse.nsf/eng/rs00585.html.

Innovation Science and Economic Development Canada, 2014. Cost-Benefit Analysis of the Canada Small Business Financing Program. Available at: https://www.ic.gc.ca/eic/site/061.nsf/eng/02918.html [Accessed March 28, 2016].

Institute for Building Efficiency, 2013. Green Building Rating Systems Japan. Available at: http://www.institutebe.com/InstituteBE/media/Library/Resources/Green Buildings/Fact-Sheet_Green-Building-Ratings_JAPAN.pdf [Accessed December 12, 2015].

International Energy Agency, 2013. *Technology Roadmap*, Paris, France.

International Organization for Standardization, 2007. *ISO 15686-5 Buildings and constructed assets - Service life planning: Part 5, Life-cycle costing*, Geneva, Switzerland.

International Organization for Standardization, 2011. No Title. Available at: http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=45798 [Accessed May 25, 2015].

Ireland, R., Fearon, P. & Hawker, L., 2008. *Highway Asset Management Quick Start Guidance Note Levels of Service Table of Contents*, London, UK.

Jafari, A. & Valentin, V., 2015. Decision-making life-cycle cost analysis model for energy-efficient housing retrofits. *International Journal of Sustainable Building Technology and Urban Development*, 6(3), pp.173–187. Available at: http://www.tandfonline.com/doi/full/10.1080/2093761X.2015.1074948.

Janda, K.B., 2014. Building communities and social potential: Between and beyond organizations and individuals in commercial properties. *Energy Policy*, 67, pp.48–55. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421513008628 [Accessed October 14, 2014].

Jiang, P. et al., 2013. Analysing co-benefits of the energy conservation and carbon reduction in China’s large commercial buildings. *Journal of Cleaner Production*, 58, pp.112–120. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0959652613002850 [Accessed June 2, 2014].

Jiang, P. & Tovey, K., 2010. Overcoming barriers to implementation of carbon reduction strategies in large commercial buildings in China. *Building and Environment*, 45(4), pp.856–864. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132309002479 [Accessed May 29, 2014].

Jiang, P. & Tovey, N.K., 2009. Opportunities for low carbon sustainability in large commercial buildings in China. *Energy Policy*, 37(11), pp.4949–4958. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421509004741 [Accessed May 26, 2014].

Kamali, M. & Hewage, K.N., 2015. Performance Indicators for Sustainability Assessment of Buildings. In *Proceedings of ICSC15: The Canadian Society for Civil Engineering 5th International/11th Construction Specialty Conference*. Vancouver, BC: Canadian Society of Civil Engineers, pp. 1–11.

Kamilaris, A. et al., 2014. A literature survey on measuring energy usage for miscellaneous electric loads in offices and commercial buildings. *Renewable and Sustainable Energy Reviews*, 34, pp.536–550. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032114001981 [Accessed September 5, 2014].

Kang, D. & Lansey, K., 2014. Multiperiod Planning of Water Supply Infrastructure Based on Scenario Analysis. *Journal of Water Resources Planning and Management*, 140(1), pp.40–54. Available at: http://ascelibrary.org/doi/abs/10.1061/(ASCE)WR.1943-

5452.0000310%5Cnhttp://ascelibrary.org/doi/10.1061/(ASCE)WR.1943-5452.0000310.

Kang, D. & Lansey, K., 2013. Scenario-Based Robust Optimization of Regional Water and Wastewater Infrastructure. *Journal of Water Resources Planning and Management*, 139(3), pp.325–338. Available at: http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000236%5Cnhttp://ascelibrary.org/doi/pdf/10.1061/(ASCE)WR.1943-5452.0000236.

Karunarathna, W. et al., 2015. Bridge deterioration modeling by Markov Chain Monte Carlo (MCMC) simulation method Bridge deterioration modeling by Markov Chain Monte Carlo (MCMC). In P.W.Tse et al., eds. *Proceedings of the 8th World Congress on Engineering Asset Management & the 3rd International Conference on Utility Management & Safety*. Switzerland: Springer International Publishing, pp. 545–556.

Keshavarzrad, P., 2015. *Optimising Asset Management of Community Buildings*. RMIT.

Keshavarzrad, P., Setunge, S. & Zhang, G., 2014. Deterioration Prediction of Building components. In *Sustainability In Public Works Conference*. Sydney, Australia: Institute of Public Works Engineering Australasia, pp. 1–9.

Khan, N. & Abas, N., 2011. Comparative study of energy saving light sources. *Renewable and Sustainable Energy Reviews*, 15(1), pp.296–309. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032110002522 [Accessed September 4, 2014].

Khan, Z., Moselhi, O. & Zayed, T., 2014. Identifying Rehabilitation Options for Optimum Improvement in Municipal Asset Condition. *Journal of Infrastructure Systems*, 21(2), p.4014037.

Khan, Z., Moselhi, O. & Zayed, T., 2009. Keywords: Analytical Hierarchy Process, Asset Management, Level of Service, Performance Indicator. In *Pipelines 2009*. ASCE, pp. 1463–1472.

Khatri, K.B., Vairavamoorthy, K. & Akinyemi, E., 2011. Framework for Computing a Performance Index for Urban Infrastructure Systems Using a Fuzzy Set Approach. *Journal of Infrastructure Systems*, 17(December), pp.163–175.

Kim, J. et al., 2016. An optimization model for selecting the optimal green systems by considering the thermal comfort and energy consumption. *Applied Energy*, 169, pp.682–695. Available at: http://dx.doi.org/10.1016/j.apenergy.2016.02.032.

Kircher, K. et al., 2010. Cleanroom energy efficiency strategies: Modeling and simulation.

Energy and Buildings, 42(3), pp.282–289. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778809002187 [Accessed August 5, 2014].

Kneifel, J., 2011. Beyond the code: Energy, carbon, and cost savings using conventional technologies. *Energy and Buildings*, 43(4), pp.951–959. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778810004603 [Accessed September 8, 2014].

Kneifel, J., 2010. Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. *Energy and Buildings*, 42(3), pp.333–340. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778809002254 [Accessed May 5, 2014].

Kovacic, I., Summer, M. & Achammer, C., 2015. Strategies of building stock renovation for ageing society. *Journal of Cleaner Production*, 88, pp.349–357. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0959652614004430.

Kumbaroglu, G. & Madlener, R., 2012. Evaluation of economically optimal retrofit investment options for energy savings in buildings. *Energy and Buildings*, 49, pp.327–334.

Kuusk, K., Kalamees, T. & Maivel, M., 2014. Cost effectiveness of energy performance improvements in Estonian brick apartment buildings. *Energy and Buildings*, 77, pp.313–322. Available at: http://dx.doi.org/10.1016/j.enbuild.2014.03.026.

Lacasse, M.A. et al., 2008. Optimization of the building maintenance management process using a markovian model. In *11th International Conference on the Durability of Building Materials and Components*. Istanbul, Turkey, pp. 1–9.

Lai, J.H.K. & Yik, F.W.H., 2009. Perception of importance and performance of the indoor environmental quality of high-rise residential buildings. *Building and Environment*, 44(2), pp.352–360.

Lai, J.H.K.K. & Yik, F.W.H.H., 2011. An analytical method to evaluate facility management services for residential buildings. *Building and Environment*, 46(1), pp.165–175. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132310002179.

Lam, J.C., 2000. Shading e € ects due to nearby buildings and energy implications. *Energy Conversion and Management*, 41, pp.647–659.

Lam, J.C. & Li, D.H.W., 2003. Electricity consumption characteristics in shopping malls in subtropical climates. , 44, pp.1391–1398.

Lavy, S. et al., 2014a. Key performance indicators for facility performance assessment:

simulation of core indicators. *Construction Management and Economics*, 32(12), pp.1183–1204.

Lavy, S. et al., 2014b. Key performance indicators for facility performance assessment: simulation of core indicators. *Construction Management and Economics*, 32(12), pp.1183–1204. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84917680003&partnerID=40&md5=bd8b70bea37d5aa941726e7e270d3d6b%5Cnhttp://www.tandfonline.com/doi/abs/10.1080/01446193.2014.970208.

Leal, V.M.S. et al., 2014a. Energy and economic analysis of building retrofit and energy offset scenarios for Net Zero Energy Buildings. *Advances in Building Energy Research*, 9(1), pp.120–139. Available at: http://www.tandfonline.com/doi/abs/10.1080/17512549.2014.944567#.VTSu1vmUeWs.

Leal, V.M.S. et al., 2014b. Energy and economic analysis of building retrofit and energy offset scenarios for Net Zero Energy Buildings. *Advances in Building Energy Research*, 9(1), pp.120–139.

Leaman, A. & Bordass, B., 2001. Assessing building performance in use 4: the Probe occupant surveys and their implications. *Building Research & Information*, 29(2), pp.129–143.

Lee, E. et al., 2002. *High-Performance Commercial Building Façades*, Berkeley, CA. Available at: http://gaia.lbl.gov/hpbf/main.html.

Lee, S.H. et al., 2015a. Energy retrofit analysis toolkits for commercial buildings: A review. *Energy*, 89, pp.1087–1100. Available at: http://dx.doi.org/10.1016/j.energy.2015.06.112.

Lee, S.H. et al., 2015b. Energy retrofit analysis toolkits for commercial buildings: A review. *Energy*, 89, pp.1087–1100.

Lee, W.L. et al., 2001. Energy saving by realistic design data for commercial buildings in Hong Kong. *Applied Energy*, 70(2000), pp.59–75.

Lee, W.L. & Lee, S.H., 2007. Developing a simplified model for evaluating chiller-system configurations. *Applied Energy*, 84(3), pp.290–306. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261906001036 [Accessed November 9, 2014].

Lee, W.L. & Yik, F.W.H., 2002. Regulatory and voluntary approaches for enhancing energy efficiencies of buildings in Hong Kong. *Applied Energy*, 71(4), pp.251–274. Available at:

http://linkinghub.elsevier.com/retrieve/pii/S0306261902000144.

Lehmann, B., Dorer, V. & Koschenz, M., 2007. Application range of thermally activated building systems tabs. *Energy and Buildings*, 39(5), pp.593–598. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778806002349 [Accessed November 13, 2014].

Lepkova, N. & Ūselis, R., 2013. Development of a Quality Criteria System for Facilities Management Services in Lithuania. *Procedia Engineering*, 57, pp.697–706.

Li, C.S. & Guo, S.J., 2012. Life cycle cost analysis of maintenance costs and budgets for university buildings in Taiwan. *Journal of Asian Architecture and Building Engineering*, 11(1), pp.87–94. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84861599570&partnerID=tZOtx3y1.

Li, J. & Colombier, M., 2009. Managing carbon emissions in China through building energy efficiency. *Journal of environmental management*, 90(8), pp.2436–47. Available at: http://www.ncbi.nlm.nih.gov/pubmed/19344996 [Accessed January 13, 2014].

Li, X. et al., 2013. Dynamic modeling and self-optimizing operation of chilled water systems using extremum seeking control. *Energy and Buildings*, 58, pp.172–182. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778812006597 [Accessed November 4, 2014].

Li, Y.M. & Wu, J.Y., 2010. Energy simulation and analysis of the heat recovery variable refrigerant flow system in winter. *Energy and Buildings*, 42(7), pp.1093–1099. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778810000307 [Accessed October 7, 2014].

Lin, H.-W. & Hong, T., 2013. On variations of space-heating energy use in office buildings. *Applied Energy*, 111, pp.515–528. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261913004418 [Accessed November 11, 2014].

Lin, J. & Young, D., 2009. *Energy Efficiency in Canadian Commercial Buildings : Evidence from 2000 and 2005*, Edmonton,AB.

Lindgren, M. & Bandhold, H., 2009. *Scenario planning : the link between future and strategy*, Palgrave Macmillan UK.

Liu, J. et al., 2010. Efficiency of energy recovery ventilator with various weathers and its energy saving performance in a residential apartment. *Energy and Buildings*, 42(1), pp.43–49. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778809001509 [Accessed September 22, 2014].

Lollini, R., Danza, L. & Meroni, I., 2010. Energy efficiency of a dynamic glazing system. *Solar Energy*, 84(4), pp.526–537. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0038092X09002977 [Accessed July 25, 2014].

Lougheed, T., 2014. Hidden Blue Hazard ? *Environ Health Perspectives*, 122(3), p.2014.

Magnier, L. & Haghighat, F., 2010. Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network. *Building and Environment*, 45(3), pp.739–746. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132309002091.

Mago, P.J. & Smith, A.D., 2012. Evaluation of the potential emissions reductions from the use of CHP systems in different commercial buildings. *Building and Environment*, 53, pp.74–82. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132312000157 [Accessed October 28, 2014].

Mahbub, A.S., Kua, H.-W. & Lee, S.-E., 2010. A total building performance approach to evaluating building acoustics performance. *Architectural Science Review*, 53(2), pp.213–223. Available at: http://www.tandfonline.com/doi/abs/10.3763/asre.2009.0032.

Maheshwari, G.P. et al., 2001. Programmable thermostat for energy saving. *Energy and Buildings*, 33(February 2000), pp.667–672.

Mahlia, T.M.I., Razak, H.A. & Nursahida, M.A., 2011. Life cycle cost analysis and payback period of lighting retrofit at the University of Malaya. *Renewable and Sustainable Energy Reviews*, 15(2), pp.1125–1132. Available at: http://dx.doi.org/10.1016/j.rser.2010.10.014.

Maile, T., Fischer, M. & Bazjanac, V., 2007. *Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective*, Stanford, CA.

Malatji, E.M., Zhang, J. & Xia, X., 2013a. A multiple objective optimisation model for building energy efficiency investment decision. *Energy and Buildings*, 61, pp.81–87. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.01.042.

Malatji, E.M., Zhang, J. & Xia, X., 2013b. A multiple objective optimisation model for building energy efficiency investment decision. *Energy and Buildings*, 61, pp.81–87.

Manitoba Hydro, 2016. Current natural gas rates. Available at:

https://www.hydro.mb.ca/regulatory_affairs/energy_rates/natural_gas/current_rates.shtml [Accessed July 14, 2016].

Manitoba Hydro, 2015. Utility rate comparisons. Available at: https://www.hydro.mb.ca/regulatory_affairs/energy_rates/electricity/utility_rate_comp.shtml [Accessed June 18, 2016].

Mann, S., Harris, I. & Harris, J., 2006. The development of urban renewable energy at the existential technology research center (ETRC) in Toronto, Canada. *Renewable and Sustainable Energy Reviews*, 10(6), pp.576–589. Available at: http://linkinghub.elsevier.com/retrieve/pii/S136403210500002X [Accessed September 30, 2014].

Manz, H. & Frank, T., 2005. Thermal simulation of buildings with double-skin façades. *Energy and Buildings*, 37(11), pp.1114–1121. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778805001052 [Accessed July 30, 2014].

Martin, C., 2013. Generating low-cost national energy benchmarks: A case study in commercial buildings in Cape Town, South Africa. *Energy and Buildings*, 64, pp.26–31. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813002314 [Accessed August 22, 2014].

Martinaitis, V., Kazakevi??ius, E. & Vitkauskas, A., 2007. A two-factor method for appraising building renovation and energy efficiency improvement projects. *Energy Policy*, 35(1), pp.192–201.

Masuda, H. & Claridge, D.E., 2014. Statistical modeling of the building energy balance variable for screening of metered energy use in large commercial buildings. *Energy and Buildings*, 77, pp.292–303. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778814002990 [Accessed August 8, 2014].

McArthur, J.J. & Jofeh, C.G.H., 2015. Strategic Retrofit Investment from the Portfolio to the Building Scale: A Framework for Identification and Evaluation of Potential Retrofits. *Procedia Engineering*, 118, pp.1068–1076.

McDiarmid, M., 2015. Canada sets carbon emissions reduction target of 30% by 2030.

McGrath, T. et al., 2013. Retrofit versus new-build house using life-cycle assessment. *Proceedings of the ICE - Engineering Sustainability*, 166(3), pp.122–137.

Medrano, M. et al., 2008. Integration of distributed generation systems into generic types of commercial buildings in California. *Energy and Buildings*, 40(4), pp.537–548. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778807001363 [Accessed July 31, 2014].

Meissner, D., 2015. B.C. Will Fail To Meet Greenhouse Gas Reduction Targets: Report.

Melo, a. P. et al., 2012. Assessing the accuracy of a simplified building energy simulation model using BESTEST: The case study of Brazilian regulation. *Energy and Buildings*, 45, pp.219–228. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778811005470 [Accessed August 18, 2014].

Melo, a. P., Sorgato, M.J. & Lamberts, R., 2014. Building energy performance assessment: Comparison between ASHRAE standard 90.1 and Brazilian regulation. *Energy and Buildings*, 70, pp.372–383. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813007974 [Accessed October 20, 2014].

Menassa, C.C., 2011. Evaluating sustainable retrofits in existing buildings under uncertainty. *Energy and Buildings*, 43(12), pp.3576–3583. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778811004324 [Accessed July 29, 2014].

Min, Z., Morgenstern, P. & Marjanovic-Halburd, L., 2016. Facilities management added value in closing the energy performance gap. *International Journal of Sustainable Built Environment*, 5(2), pp.197–209. Available at: http://dx.doi.org/10.1016/j.ijsbe.2016.06.004.

Ministry of Environment BC, 2016. *BC Best practices methodology for quantifying green house gas emissions*, Victoria, BC. Available at: http://www2.gov.bc.ca/assets/gov/environment/climate-change/policy-legislation-and-responses/carbon-neutral-government/measure-page/2016-2017_bc_best_practices_methodology_for_quantifying_ghg_emissions.pdf.

Ministry of Environment BC, 2012. *British Columbia Greenhouse Gas Inventory Report 2012*, Victoria, BC.

Ministry of Environment BC, 2007. Ministry of Environment Climate Action Secretariat. Available at: http://www.env.gov.bc.ca/cas/.

Mirza, S., 2007. *The Comming Collapse of Canadas Municipal Infrastructure*, Ottawa ON: Federation of Canadian Municipalities.

Mishra, S., Khasnabis, S. & Dhingra, S.L., 2013a. A simulation approach for estimating value at risk in transportation infrastructure investment decisions. *Research in Transportation*

Economics, 38(1), pp.128–138. Available at: http://dx.doi.org/10.1016/j.retrec.2012.05.009.

Mishra, S., Khasnabis, S. & Dhingra, S.L., 2013b. A simulation approach for estimating value at risk in transportation infrastructure investment decisions. *Research in Transportation Economics*, 38(1), pp.128–138.

Mistry, V., 2007. Briefing: BREEAM—making what is important measurable. *Proceedings of the ICE - Engineering Sustainability*, 160(March), pp.11–14.

Mohareb, E. a. & Kennedy, C. a., 2014. Scenarios of technology adoption towards low-carbon cities. *Energy Policy*, 66, pp.685–693. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421513010938 [Accessed October 19, 2014].

Morcous, G. et al., 2002. Case-Based Reasoning System for Modeling Infrastructure Deterioration. , (April), pp.104–114.

Morcous, G., 2000. *Case Based Reasoning for Modeling Bridge Deterioration*. Concordia University.

Morcous, G., Lounis, Z. & Mirza, M., 2003. Identification of environmental categories for Markovian deterioration models of bridge decks. *Journal of Bridge Engineering*, 8(6), pp.353–361.

Moretti, E., Zinzi, M. & Belloni, E., 2014. Polycarbonate panels for buildings: Experimental investigation of thermal and optical performance. *Energy and Buildings*, 70, pp.23–35. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813007524 [Accessed November 19, 2014].

Morrissey, J. & Horne, R.E., 2011. Life cycle cost implications of energy efficiency measures in new residential buildings. *Energy and Buildings*, 43(4), pp.915–924. Available at: http://dx.doi.org/10.1016/j.enbuild.2010.12.013.

Naaz, S., Alam, A. & Biswas, R., 2011. Effect of Different Defuzzification Methods in a Fuzzy Based Load Balancing Application. *International Journal of Computer Science Issues (IJCSI)*, 8(5), pp.261–267.

Nadel, S., 2015. Looking to the future of energy efficiency markets and programs. Available at: http://aceee.org/blog/2015/02/looking-future-energy-efficiency-mark [Accessed March 4, 2017].

Naimaster, E.J. & Sleiti, a. K., 2013. Potential of SOFC CHP systems for energy-efficient commercial buildings. *Energy and Buildings*, 61, pp.153–160. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778812006081 [Accessed August 27, 2014].

Nair, S. et al., 2014. Water-energy-greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods. *Resources, Conservation and Recycling*, 89, pp.1–10. Available at: http://dx.doi.org/10.1016/j.resconrec.2014.05.007.

Namini, S.B. et al., 2014. Managerial sustainability assessment tool for Iran's buildings. *Proceedings of the ICE - Engineering Sustainability*, 167(1), pp.12–23. Available at: http://www.icevirtuallibrary.com/content/article/10.1680/ensu.12.00041.

NASA, 2000. *Reliability centred maintenace guide*, Washington, DC. Available at: http://www.hq.nasa.gov/office/codej/codejx/Assets/Docs/RCMGuideMar2000.pdf.

National Academy of Sciences, 2009. *America's Energy Future: Technology and Transformation*, Washington, DC: National Academy of Sciences.

National Institute of Building Sciences, 2012. Cost–Effective. Available at: https://www.wbdg.org/design/cost_effective.php [Accessed August 15, 2016].

National Institute of Building Sciences, 2015. Secure / Safe. Available at: https://www.wbdg.org/design/secure_safe.php [Accessed August 15, 2016].

National Research Council et al., 2004. *Intelligent Sustainment and Renewal of Department of Energy Facilities and Infrastruccture*, Washington, DC: National Academies Press.

Natural Resources Canada, 2014a. A model for change. Available at: http://www.nrcan.gc.ca/energy/efficiency/buildings/embp/4005.

Natural Resources Canada, 2014b. Buildings. Available at: http://www.nrcan.gc.ca/energy/efficiency/buildings/4261.

Natural Resources Canada, 2012a. Energy Efficiency Trends in Canada, 1990 to 2009. Available at: http://oee.nrcan.gc.ca/publications/statistics/trends11/chapter4.cfm?attr=0.

Natural Resources Canada, 2012b. *Survey of Commercial and Institutional Energy Use: Buildings 2009*, Ottawa, ON: Office of Energy Efficiency.

Nebraska Department of Roads, 2011. *Developing Deterioration Models for Nebrasaka Bridges*, Lincoln, NE.

Ng, L.C. et al., 2013. Multizone airflow models for calculating infiltration rates in commercial reference buildings. *Energy and Buildings*, 58, pp.11–18. Available at:

http://linkinghub.elsevier.com/retrieve/pii/S0378778812006494 [Accessed November 18, 2014].

Ng, P.K., Mithraratne, N. & Kua, H.W., 2013. Energy analysis of semi-transparent BIPV in Singapore buildings. *Energy and Buildings*, 66, pp.274–281. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813004179 [Accessed September 5, 2014].

Nguyen, B.K. & Altan, H., 2011. Comparative Review of Five Sustainable Rating Systems. *Procedia Engineering*, 21(0), pp.376–386. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1877705811048636.

Nikolaou, T., Kolokotsa, D. & Stavrakakis, G., 2011. Review on methodologies for energy benchmarking, rating and classification of buildings. *Advances in Building Energy Research*, 5(1), pp.53–70. Available at: http://www.tandfonline.com/doi/abs/10.1080/17512549.2011.582340 [Accessed April 29, 2014].

Nilashi, M. et al., 2015. A knowledge-based expert system for assessing the performance level of green buildings. *Knowledge-Based Systems*, 86, pp.194–209. Available at: http://dx.doi.org/10.1016/j.knosys.2015.06.009.

O'Donnell, J. et al., 2013. Building performance optimization using cross-domain scenario modeling, linked data, and complex event processing. *Building and Environment*, 62, pp.102–111. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132313000346 [Accessed October 2, 2014].

Office of Government Commerce, 2007. *Service transition*, Norwich: The stationary office.

Office of Housing and Construction Standards, 2016. *Energy Step Code Implementation Recommendations*, Burnaby, BC. Available at: http://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/construction-industry/building-codes-and-standards/reports/step_code_sciwg_report_final.pdf.

Osman, H., 2005. Risk-Based Life-Cycle Cost Analysis of Privatized Infrastructure. *Transportation Research Record*, 1924(1924), pp.192–196.

Oyedele, L.O. et al., 2012. Total Building Performance Approach in Building Evaluation : Case Study of an Office Building in Singapore. *Journal of Energy Engineering*, 138(March), pp.25–30.

Parasuraman, A., Zeithaml, V.A. & Berry, L.L., 2016. A Conceptual Model of Service Quality and Its Implications for Future Research. *Journal of Marketing*, 49(4), pp.41–50.

Parkinson, A. & Guthrie, P., 2014. Evaluating the energy performance of buildings within a value at risk framework with demonstration on UK offices. *Applied Energy*, 133, pp.40–55. Available at: http://dx.doi.org/10.1016/j.apenergy.2014.07.074.

Parrat, J. et al., 2012. Assessment of occupational and public exposure to trichloramine in Swiss indoor swimming pools: a proposal for an occupational exposure limit. *Annals of Occupational Hygiene*, 56(3), pp.264–277.

Pedrycz, W. & Gomide, F., 2007. *Fuzzy Systems Engineering: Toward Human-Centric Computing*, Hoboken, N.J: John Wiley & Sons.

Peng, C., Wang, L. & Zhang, X., 2014. DeST-based dynamic simulation and energy efficiency retrofit analysis of commercial buildings in the hot summer/cold winter zone of China: A case in Nanjing. *Energy and Buildings*, 78, pp.123–131. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778814003338 [Accessed August 1, 2014].

Pérez-Lombard, L. et al., 2011. A review of HVAC systems requirements in building energy regulations. *Energy and Buildings*, 43(2–3), pp.255–268. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778810003774 [Accessed July 18, 2014].

Pérez-Lombard, L., Ortiz, J. & Pout, C., 2008. A review on buildings energy consumption information. *Energy and Buildings*, 40(3), pp.394–398. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778807001016 [Accessed March 20, 2014].

Peterman, A., Kourula, A. & Levitt, R., 2012. A roadmap for navigating voluntary and mandated programs for building energy efficiency. *Energy Policy*, 43, pp.415–426. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421512000316 [Accessed August 16, 2014].

Phelan, M., 2015. *Square Foot Costs 2015 Book*, Norwell, MA: RSMeans.

Picco, M., Lollini, R. & Marengo, M., 2014. Towards energy performance evaluation in early stage building design: A simplification methodology for commercial building models. *Energy and Buildings*, 76, pp.497–505. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778814002369 [Accessed August 14,

2014].

Pitts, A., 2008. Future proof construction—Future building and systems design for energy and fuel flexibility. *Energy Policy*, 36(12), pp.4539–4543. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421508004783 [Accessed September 6, 2014].

Plebankiewicz, E., Zima, K. & Wieczorek, D., 2015. Review of methods of determining the life cycle cost of buildings. In *Creative Construction Conference*. Krakow, Polad, pp. 309–316.

Poel, B., van Cruchten, G. & Balaras, C. a., 2007. Energy performance assessment of existing dwellings. *Energy and Buildings*, 39(4), pp.393–403. Available at: http://linkinghub.elsevier.com/retrieve/pii/S037877880600212X [Accessed April 30, 2014].

Porter, M.E., 1995. *Competitive Advantage: Creating and Sustaining Superior Performance*, New York, NY: Free Press.

Priyadarsini, R., 2014. Energy performance of aquatic facilities in Victoria , Australia. *Facilities*, 32(9/10), pp.565–580.

Prozzi, J.A. & Madanat, S.M., *A Non-linear Model for Predicting Pavement Serviceability*,

Radhi, H., 2009. Can envelope codes reduce electricity and CO2 emissions in different types of buildings in the hot climate of Bahrain? *Energy*, 34(2), pp.205–215. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360544208003216 [Accessed August 22, 2014].

Rahman, S. & Vanier, D.J., 2004. Life cycle cost analysis as a decision support tool for managing municipal infrastructure. In *CIB 2004 Triennial Congress*. Toronto, ON: CIB publication, p. 13.

Rajani, B.B., Kleiner, Y. & Sadiq, R., 2006. Translation of pipe inspection results into condition rating using fuzzy synthetic valuation technique. *Journal of Water Supply Research and Technology: Aqua*, 55(1), pp.11–24.

Ramana, a. S. et al., 2014. Experimental investigation of the LHS system and comparison of the stratification performance with the SHS system using CFD simulation. *Solar Energy*, 103, pp.378–389. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0038092X14000863 [Accessed August 30, 2014].

Rankin, R., Rousseau, P.G. & van Eldik, M., 2004. Demand side management for commercial buildings using an inline heat pump water heating methodology. *Energy Conversion and*

Management, 45(9–10), pp.1553–1563. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0196890403002401 [Accessed October 25, 2014].

Rezaie, B., Esmailzadeh, E. & Dincer, I., 2011. Renewable energy options for buildings: Case studies. *Energy and Buildings*, 43(1), pp.56–65. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778810002884 [Accessed October 4, 2014].

Richardson, B.A., 2000. *Defects and Deterioration in Buildings*, New York, NY: Roultedge.

Ricker, E., 2006. *Assessing methods for predicting retrofit energy savings in buildings: Case study for a Norwegian school*. Massachusetts Institute of Technology.

Rincón, L. et al., 2013. Evaluation of the environmental impact of experimental buildings with different constructive systems using Material Flow Analysis and Life Cycle Assessment. *Applied Energy*, 109, pp.544–552. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261913001463.

Roberts, S., 2008. Altering existing buildings in the UK. *Energy Policy*, 36(12), pp.4482–4486. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421508004692 [Accessed July 11, 2014].

Ross, T.J., 2005. *Fuzzy logic with engineering applications*, Hoboken, N.J: John Wiley & Sons.

Ross, T.J., 2010. *Fuzzy Logic with Engineering Applications* 3rd Editio., Hoboken, N.J: John Wiley & Sons.

Ruan, Y. et al., 2009. Optimal option of distributed generation technologies for various commercial buildings. *Applied Energy*, 86(9), pp.1641–1653. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261909000270 [Accessed October 1, 2014].

Ruparathna, R., Hewage, K. & Sadiq, R., 2015. Assessment of the level of service (LOS) of public recreational centre buildings : an uncertainty based approach. In *5th International Construction Specialty Conference of the Canadian Society for Civil Engineering (ICSC).* Vancouver, BC: Canadian Society of Civil Engineers, pp. 1–10.

Ruparathna, R., Hewage, K. & Sadiq, R., 2017a. Developing a Level of Service (LOS) Index for Operational Management of Public Buildings. *Sustainable Cities and Society*, p.In Press.

Ruparathna, R., Hewage, K. & Sadiq, R., 2017b. Economic evaluation of building energy retrofits: A fuzzy based approach. *Energy and Buildings*, 139, pp.395–406.

Ruparathna, R., Hewage, K. & Sadiq, R., 2016. Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renewable and Sustainable Energy Reviews*, 53, pp.1032–1045. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032115010540.

Ruparathna, R., Hewage, K. & Sadiq, R., 2017c. Rethinking investment planning and optimizing net zero emission buildings. *Clean Technologies and Environmental Policy*, pp.1–14.

Rupp, R.F. & Ghisi, E., 2014. What is the most adequate method to assess thermal comfort in hybrid commercial buildings located in hot-humid summer climate? *Renewable and Sustainable Energy Reviews*, 29, pp.449–462. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032113006515 [Accessed November 19, 2014].

Rysanek, A.M. & Choudhary, R., 2013. Optimum building energy retrofits under technical and economic uncertainty. *Energy and Buildings*, 57, pp.324–337.

Sabapathy, A. et al., 2010. Energy efficiency benchmarks and the performance of LEED rated buildings for Information Technology facilities in Bangalore, India. *Energy and Buildings*, 42(11), pp.2206–2212. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778810002306 [Accessed August 22, 2014].

Sadeghi, N., Fayek, A.R. & Pedrycz, W., 2010. Fuzzy Monte Carlo simulation and risk assessment in construction. *Computer-Aided Civil and Infrastructure Engineering*, 25(4), pp.238–252.

Saidur, R. et al., 2011. Chillers energy consumption, energy savings and emission analysis in an institutional buildings. *Energy*, 36(8), pp.5233–5238. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360544211004129 [Accessed November 12, 2014].

Samer, B., Matthew, M.M. & Mccarthr, P.S., 1997. Probabilistic infrastrucutre deterioration models with panel data. *Journal of Infrastructure Systems*, 3(1), pp.4–9.

Sanaye, S., Meybodi, M.A. & Chahartaghi, M., 2010. Modeling and economic analysis of gas engine heat pumps for residential and commercial buildings in various climate regions of Iran. *Energy and Buildings*, 42(7), pp.1129–1138. Available at:

http://linkinghub.elsevier.com/retrieve/pii/S0378778810000356 [Accessed October 4, 2014].

Sarbu, I. & Sebarchievici, C., 2014. General review of ground-source heat pump systems for heating and cooling of buildings. *Energy and Buildings*, 70, pp.441–454. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813007858 [Accessed November 2, 2014].

SaskEnergy, 2016. Commercial Rates. Available at: http://www.saskenergy.com/business/comrates_curr.asp [Accessed July 14, 2016].

Sasmita, M., 2010. *Engineering Economics and Costing*, New Delhi: PHI Learning.

Scheidegger, a et al., 2011. Network condition simulator for benchmarking sewer deterioration models. *Water research*, 45(16), pp.4983–94. Available at: http://www.ncbi.nlm.nih.gov/pubmed/21803394 [Accessed February 9, 2014].

Schein, J. et al., 2006. A rule-based fault detection method for air handling units. *Energy and Buildings*, 38(12), pp.1485–1492. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778806001034 [Accessed November 16, 2014].

Schneider, J. et al., 2006. Asset management techniques. *International Journal of Electrical Power & Energy Systems*, 28(9), pp.643–654. Available at: https://apps.webofknowledge.com/full_record.do?product=UA&search_mode=GeneralSearch&qid=3&SID=1DT7NcQle1e1FcSJ4FO&page=1&doc=1%5Cnhttp://linkinghub.elsevier.com/retrieve/pii/S0142061506000834.

Schoemaker, P.J.H., 1995. Scenario Planning: A Tool for Strategic Thinking. *Sloan Management Review*, 36(2), pp.25–40.

Scholten, L. et al., 2015. Tackling uncertainty in multi-criteria decision analysis - An application to water supply infrastructure planning. *European Journal of Operational Research*, 242(1), pp.243–260. Available at: http://dx.doi.org/10.1016/j.ejor.2014.09.044.

Schroeder, M.J. & Lambert, J.H., 2011. Scenario-based multiple criteria analysis for infrastructure policy impacts and planning. *Journal of Risk Research*, 14(2), pp.191–214. Available at: http://www.tandfonline.com/doi/abs/10.1080/13669877.2010.515314.

Seiler-Hausmann, J.-D., 2004. *Eco-Efficiency and Beyond: Towards the Sustainable Enterprise*, Sheffield, UK: Greenleaf Publishing Limited.

Sezgen, O. & Koomey, J.G., 2000. Interactions between lighting and space conditioning energy use in US commercial buildings. , 25, pp.793–805.

Shaheen, A. a., Fayek, A.R. & AbouRizk, S.M., 2007. Fuzzy Numbers in Cost Range Estimating. *Journal of Construction Engineering and Management*, 133(4), pp.325–334.

Shameri, M. a. et al., 2011. Perspectives of double skin façade systems in buildings and energy saving. *Renewable and Sustainable Energy Reviews*, 15(3), pp.1468–1475. Available at: http://dx.doi.org/10.1016/j.rser.2010.10.016.

Shao, Y., Geyer, P. & Lang, W., 2014. Integrating requirement analysis and multi-objective optimization for office building energy retrofit strategies. *Energy and Buildings*, 82, pp.356–368. Available at: http://dx.doi.org/10.1016/j.enbuild.2014.07.030.

Sharma, V., Al-hussein, M., et al., 2008. Municipal Infrastructure Asset Levels of Service Assessment. , (September), pp.193–200.

Sharma, V., Al-Hussein, M., et al., 2008. Municipal Infrastructure Asset Levels of Service Assessment for Investment Decisions Using Analytic Hierarchy Process. *Journal of Infrastructure Systems*, 14(3), pp.193–200. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-50149119055&partnerID=tZOtx3y1.

El shenawy, A. & Zmeureanu, R., 2013. Exergy-based index for assessing the building sustainability. *Building and Environment*, 60, pp.202–210. Available at: http://dx.doi.org/10.1016/j.buildenv.2012.10.019.

Shohet, I.M., 2003. Building evaluation methodology for setting maintenance priorities in hospital buildings. *Construction Management and Economics*, 21(7), pp.681–692.

Shoolestani, A. et al., 2015. SocioBIM : BIM-to-end user interaction for sustainable building operations and facility asset management. *5th International/11th Construction Specialty Conference*, (2014), pp.3261–3266.

Siu, G.K.W., Bridge, A. & Skitmore, M., 2001. Assessing the service quality of building maintenance providers : mechanical and engineering services. *Construction Management and Economics*, 19(7), pp.719–726.

Srinivasan, R.S. et al., 2014. Comparison of energy-based indicators used in life cycle assessment tools for buildings. *Building and Environment*, 79, pp.138–151. Available at:

http://linkinghub.elsevier.com/retrieve/pii/S0360132314001425.

Stantec Consulting Ltd., 2008. *Feasibility Study District of Elkford*, Elkford,BC.

Steven Winter Associates Inc., 2014. Net Zero Energy Buildings. Available at: https://www.wbdg.org/resources/netzeroenergybuildings.php [Accessed January 8, 2016].

Sun, Y., Wang, S. & Huang, G., 2010. A demand limiting strategy for maximizing monthly cost savings of commercial buildings. *Energy and Buildings*, 42(11), pp.2219–2230. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778810002343 [Accessed October 23, 2014].

Susorova, I. et al., 2013. The effect of geometry factors on fenestration energy performance and energy savings in office buildings. *Energy and Buildings*, 57, pp.6–13. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778812005518 [Accessed September 2, 2014].

Sydney Water, 2011. *Best practice guidelines for water management in aquatic leisure centres*, Sydney, Australia.

Talyor, R. a. & Miner, M., 2014. A metric for characterizing the effectiveness of thermal mass in building materials. *Applied Energy*, 128, pp.156–163. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261914004140 [Accessed October 21, 2014].

Tesfamariam, S., Rajani, B. & Sadiq, R., 2006. Possibilistic approach for consideration of uncertainties to estimate structural capacity of ageing cast iron water mains. *Canadian Journal of Civil Engineering*, 33(8), pp.1050–1064.

The World Bank, 2005. *Public Services Delivery*, Washington, DC: Intronational Bank for Reconstruction and Development.

Thekdi, S.A. & Santos, J.R., 2016. Supply Chain Vulnerability Analysis Using Scenario-Based Input-Output Modeling: Application to Port Operations. *Risk Analysis*, 36(5), pp.1025–1039.

Thomas, B. a., Azevedo, I.L. & Morgan, G., 2012. Edison Revisited: Should we use DC circuits for lighting in commercial buildings? *Energy Policy*, 45, pp.399–411. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421512001656 [Accessed September 8, 2014].

Thomopoulos, N.T., 2012. *Essentials of Monte Carlo Simulation: Statistical Methods for*

Building Simulation Models, New York, NY: Springer.

Torcellini, P. et al., 2006. Zero Energy Buildings: A Critical Look at the Definition. In *ACEEE Summer Study*. Pacific Grove, CA: National Renewable Energy Laboratory.

Township of Esquimalt, 2013. Esquimalt Recreation Centre Aquatic Energy Retrofit Project. Available at: http://www.civicinfo.bc.ca/practices_innovations/l&i-ca-esquimalt.pdf [Accessed December 21, 2015].

Tran, H.U.U.D., 2007. *Investigation of deterioration models for stormwater pipe systems*. University of Victoria.

Transportation Research Board, 2006. *COOPERATIVE HIGHWAY PROGRAM*, Washington, DC: Transportation research board.

Transportation Research Board, 2013. *Transit Capacity and Quality of Service Manual*, Washington, DC: Transportation research board.

Trianti-Stourna, E. et al., 1998. Energy conservation strategies for sports centers: Part B. Swimming pools. *Energy and Buildings*, 27, pp.123–135.

Tsai, W.-H. et al., 2014. An Activity-Based Costing decision model for life cycle assessment in green building projects. *European Journal of Operational Research*, 238(2), pp.607–619. Available at: http://www.sciencedirect.com/science/article/pii/S0377221714002537.

Tulsyan, A. et al., 2013. Potential of energy savings through implementation of Energy Conservation Building Code in Jaipur city, India. *Energy and Buildings*, 58, pp.123–130. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778812006068 [Accessed September 2, 2014].

U.S. General Services Administration, 2016. Lighting. Available at: https://www.gsa.gov/portal/content/101308 [Accessed January 2, 2017].

Umer, A. et al., 2016. Sustainability assessment of roadway projects under uncertainty using Green Proforma: An index-based approach. *International Journal of Sustainable Built Environment*. Available at: http://dx.doi.org/10.1016/j.ijsbe.2016.06.002.

Union Gas, 2016. Gas Supply Charges. Available at: https://www.uniongas.com/~/media/aboutus/rates/business/rate10.pdf?la=en [Accessed July 14, 2016].

United Nations, 2004. Accessibility for the Disabled - A Design Manual for a Barrier Free Environment. Available at: http://www.un.org/esa/socdev/enable/designm/AD3-01.htm

[Accessed January 17, 2017].

United Nations Environment Programme, 2015. Why Buildings. Available at: http://www.unep.org/sbci/AboutSBCI/Background.asp [Accessed February 5, 2015].

United Nations Framework Convention on Climate Change, 2016. Historic Paris Agreement on Climate Change. Available at: http://newsroom.unfccc.int/unfccc-newsroom/finale-cop21/ [Accessed March 16, 2016].

United States Environmental Protection Agency (USEPA), 2009. Buildings and their Impact on the Environment: A Statistical Summary. Available at: http://www.epa.gov/greenbuilding/pubs/gbstats.pdf.

United States Environmental Protection Agency (USEPA), 2014. Eco-Efficiency Analysis. Available at: http://www.epa.gov/sustainability/analytics/eco-efficiency.htm.

US Department of Energy, 2012a. *2011 Buildings Energy Data Book*, Washington, DC.

US Department of Energy, 2015a. *A Common Definition for Zero Energy Buildings,* Washington, DC. Available at: http://energy.gov/sites/prod/files/2015/09/f26/bto_common_definition_zero_energy_buildings_093015.pdf.

US Department of Energy, 2015b. *A Common Definition for Zero Energy Buildings,* Washington, DC.

US Department of Energy, 2015c. *An assessment of energy technologies and research oppertuinities*, Washington, DC: US Department of Energy. Available at: https://energy.gov/sites/prod/files/2015/09/f26/Quadrennial-Technology-Review-2015_0.pdf.

US Department of Energy, 2010. *Operations & Maintenance Best Practices: A Guide to Achieving Operational Efficiency*, Washington, DC. Available at: http://energy.gov/sites/prod/files/2013/10/f3/omguide_complete.pdf.

US Department of Energy, 2012b. Solar Ventilation Air Preheating. Available at: https://www.wbdg.org/resources/svap.php#om [Accessed July 11, 2016].

USEPA, 2010a. Fundamentals of Asset Management. Available at: https://www.epa.gov/sites/production/files/2016-01/documents/set-target-level-of-service.pdf [Accessed December 1, 2016].

USEPA, 2010b. Fundamentals of Asset Management.

Vijayan, A. & Kumar, A., 2005. Development of a tool for analyzing the sustainability of residential buildings in Ohio. *Environmental Progress*, 24(3), pp.238–247. Available at: http://doi.wiley.com/10.1002/ep.10095.

Vine, E., 2003. Opportunitites for promoting energy efficiency in buildings as an air quality compliance approach. *Energy*, 28(4), pp.319–341. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360544202001123 [Accessed August 28, 2014].

Vose, D., 2000. *Risk analysis: A quantitative guide*, London: Wiley publishing.

Vučićević, B. et al., 2014. Assessing the sustainability of the energy use of residential buildings in Belgrade through multi-criteria analysis. *Energy and Buildings*, 69, pp.51–61. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813006683.

Waggett, R. & Arotsky, C., 2006. Water Key Performance Indicators and benchmarks for offices and hotels. *CIRIA Publications*, C657, pp.1–14.

Wagner, A. et al., 2014. Performance analysis of commercial buildings—Results and experiences from the German demonstration program “Energy Optimized Building (EnOB).” *Energy and Buildings*, 68, pp.634–638. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813006440 [Accessed July 14, 2014].

Wallin, J., Madani, H. & Claesson, J., 2012. Run-around coil ventilation heat recovery system: A comparative study between different system configurations. *Applied Energy*, 90(1), pp.258–265. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261911003035 [Accessed November 9, 2014].

Wang, B. & Xia, X., 2015a. Optimal maintenance planning for building energy efficiency retrofitting from optimization and control system perspectives. *Energy and Buildings*, 96, pp.299–308. Available at: http://dx.doi.org/10.1016/j.enbuild.2015.03.032.

Wang, B. & Xia, X., 2015b. Optimal maintenance planning for building energy efficiency retrofitting from optimization and control system perspectives. *Energy and Buildings*, 96, pp.299–308.

Wang, B., Xia, X. & Zhang, J., 2014a. A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings. *Energy and Buildings*, 77, pp.227–235.

Available at: http://dx.doi.org/10.1016/j.enbuild.2014.03.025.

Wang, B., Xia, X. & Zhang, J., 2014b. A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings. *Energy and Buildings*, 77, pp.227–235.

Wang, G. & Song, L., 2012. Air handling unit supply air temperature optimal control during economizer cycles. *Energy and Buildings*, 49, pp.310–316. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778812001016 [Accessed October 14, 2014].

Wang, G. & Song, L., 2013. An energy performance study of several factors in air economizers with low-limit space humidity. *Energy and Buildings*, 64, pp.447–455. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813003010 [Accessed November 19, 2014].

Wang, H. & Chen, Q., 2013. A semi-empirical model for studying the impact of thermal mass and cost-return analysis on mixed-mode ventilation in office buildings. *Energy and Buildings*, 67, pp.267–274. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.08.025.

Wang, L., Chu, J. & Mao, W., 2008. An optimum condition-based replacement and spare provisioning policy based on Markov chains. *Journal of Quality in Maintenance Engineering*, 14(4), pp.387–401.

Wang, N., Chang, Y.-C. & El-Sheikh, A., 2012. Monte Carlo simulation approach to life cycle cost management. *Structure and Infrastructure Engineering*, 8(8), pp.739–746.

Wang, N., Zhang, J. & Xia, X., 2013. Desiccant wheel thermal performance modeling for indoor humidity optimal control. *Applied Energy*, 112, pp.999–1005. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261913002560 [Accessed October 29, 2014].

Wang, S., Yan, C. & Xiao, F., 2012. Quantitative energy performance assessment methods for existing buildings. *Energy and Buildings*, 55, pp.873–888. Available at: http://dx.doi.org/10.1016/j.enbuild.2012.08.037.

Wang, X., Burgess, A. & Yang, J., 2013. A scenario-based water conservation planning support system (SB-WCPSS). *Stochastic Environmental Research and Risk Assessment*, 27(3), pp.629–641.

Warnock, A.C.C., 2001. Specifying Acoustical Criteria for Buildings. *Construction Technology Update*, (50). Available at: http://www.nrc-cnrc.gc.ca/ctu-sc/files/doc/ctu-sc/ctun50_eng.pdf.

Whyte, a & Scott, D., 2010. Life-cycle costing analysis to assist design decisions: beyond 3D building information modelling. *Proceedings of the International Conference on Computing in Civil and Building Engineering*, (ii), pp.173–180. Available at: http://www.engineering.nottingham.ac.uk/icccbe/87.htm.

Wijayatunga, P.D.C. et al., 2006. Strategies to overcome barriers for cleaner generation technologies in small developing power systems: Sri Lanka case study. *Energy Conversion and Management*, 47(9–10), pp.1179–1191. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0196890405001834 [Accessed September 30, 2014].

Wireman, T., 2004. *Benchmarking Best Practices in Maintenance Management*, New York, NY: Industrial Press Inc.

Wong, N.H. & Jan, W.L.S., 2003. Total building performance evaluation of academic institution in Singapore. *Building and Environment*, 38(1), pp.161–176. Available at: http://www.sciencedirect.com/science/article/pii/S0360132302000215.

Woo, J.-H. & Menassa, C., 2014. Virtual Retrofit Model for aging commercial buildings in a smart grid environment. *Energy and Buildings*, 80, pp.424–435. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778814003867 [Accessed August 17, 2014].

Wu, H.J. et al., 2011. Life cycle energy consumption and CO2 emission of an office building in China. *The International Journal of Life Cycle Assessment*, 17(2), pp.105–118. Available at: http://link.springer.com/10.1007/s11367-011-0342-2 [Accessed April 15, 2014].

Wübbenhorst, K.L., 1986. Life cycle costing for construction projects. *Long range planning*, 19(4), pp.87–97.

Xu, D. & Qu, M., 2013. Energy, environmental, and economic evaluation of a CCHP system for a data center based on operational data. *Energy and Buildings*, 67, pp.176–186. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813005185 [Accessed September 3, 2014].

Yalcintas, M. & Kaya, A., 2009. Conservation vs. renewable energy: Cases studies from Hawaii. *Energy Policy*, 37(8), pp.3268–3273. Available at: http://linkinghub.elsevier.com/retrieve/pii/S030142150900278X [Accessed September 30,

2014].

Yamaguchi, Y., Shimoda, Y. & Mizuno, M., 2007. Transition to a sustainable urban energy system from a long-term perspective: Case study in a Japanese business district. *Energy and Buildings*, 39(1), pp.1–12. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778806001368 [Accessed October 7, 2014].

Yan, X. et al., 2014. Techno-economic and social analysis of energy storage for commercial buildings. *Energy Conversion and Management*, 78, pp.125–136. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0196890413006341 [Accessed August 29, 2014].

Yang, H., Cui, P. & Fang, Z., 2010. Vertical-borehole ground-coupled heat pumps: A review of models and systems. *Applied Energy*, 87(1), pp.16–27. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261909001743 [Accessed November 10, 2014].

Yang, K.-H. & Hwang, R.-L., 2007. An improved assessment model of variable frequency-driven direct expansion air-conditioning system in commercial buildings for Taiwan green building rating system. *Building and Environment*, 42(10), pp.3582–3588. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132306003088 [Accessed August 7, 2014].

Yang, Z. & Becerik-Gerber, B., 2014. The coupled effects of personalized occupancy profile based HVAC schedules and room reassignment on building energy use. *Energy and Buildings*, 78, pp.113–122. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778814003028 [Accessed November 19, 2014].

Yau, Y.H. & Hasbi, S., 2013. A review of climate change impacts on commercial buildings and their technical services in the tropics. *Renewable and Sustainable Energy Reviews*, 18, pp.430–441. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032112005862 [Accessed July 11, 2014].

Ye, X. et al., 2015a. Optimal maintenance planning for sustainable energy efficiency lighting retrofit projects by a control system approach. *Control Engineering Practice*, 37, pp.1–10. Available at: http://dx.doi.org/10.1016/j.conengprac.2014.12.014.

Ye, X. et al., 2015b. Optimal maintenance planning for sustainable energy efficiency lighting retrofit projects by a control system approach. *Control Engineering Practice*, 37, pp.1–10.

Yik, F.W.H., Burnett, J. & Prescott, I., 2001. Predicting air-conditioning energy consumption of a group of buildings using different heat rejection methods. *Energy and Buildings*, 33, p.151±166.

Yin, G.G. & Zhang, Q., 2000. *Discrete-Time Markov Chains*, New York, NY: Springer.

Yoon, K.P., 2008. A Probabilistic Approach to Fuzzy Engineering Economic Analysis. In C. Kahraman, ed. *Fuzzy Engineering Economics with Applications*. Berlin Heidelberg: Springer-Verlag Berlin Heidelberg.

Yu, F.W. & Chan, K.T., 2005. Advanced control of condensing temperature for enhancing the operating efficiency of air-cooled chillers. *Building and Environment*, 40(6), pp.727–737. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132304002562 [Accessed October 4, 2014].

Yu, F.W. & Chan, K.T., 2012. Improved energy management of chiller systems by multivariate and data envelopment analyses. *Applied Energy*, 92, pp.168–174. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261911007136 [Accessed November 11, 2014].

Yu, F.W. & Chan, K.T., 2007. Strategy for designing more energy efficient chiller plants serving air-conditioned buildings. *Building and Environment*, 42(10), pp.3737–3746. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132306002757 [Accessed November 11, 2014].

Yu, K., Froese, T. & Grobler, F., 2000. A development framework for data models for computer-integrated facilities management. *Automation in Construction*, 9(2), pp.145–167. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0926580599000023.

Yu, P.C.H. & Chow, W.K., 2007. A discussion on potentials of saving energy use for commercial buildings in Hong Kong. *Energy*, 32(2), pp.83–94. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360544206000715 [Accessed August 22, 2014].

Yu, S. et al., 2014. A long-term, integrated impact assessment of alternative building energy code scenarios in China. *Energy Policy*, 67, pp.626–639. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421513011166 [Accessed September 10,

2014].

Yun, T.S. et al., 2013. Evaluation of thermal conductivity for thermally insulated concretes. *Energy and Buildings*, 61, pp.125–132. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813000868 [Accessed November 18, 2014].

Zeynalian, M., Trigunarsyah, B. & Ronagh, H.R., 2013. Modification of Advanced Programmatic Risk Analysis and Management Model for the Whole Project Life Cycle ' s Risks. *Journal of Construction Engineering and Management*, 139(January), pp.51–60.

Zhang, X. & Asce, M., 2006. Markov-Based Optimization Model for Building Facilities Management. , 132(November), pp.1203–1212.

Zhang, X. & Gao, H., 2010. Optimal performance-based building facility management. *Computer-Aided Civil and Infrastructure Engineering*, 25(4), pp.269–284.

Zhao, J., Xin, Y. & Tong, D., 2012. Energy consumption quota of public buildings based on statistical analysis. *Energy Policy*, 43, pp.362–370. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421512000183 [Accessed August 10, 2014].

Zhao, J., Zhu, N. & Wu, Y., 2009. The analysis of energy consumption of a commercial building in Tianjin, China. *Energy Policy*, 37(6), pp.2092–2097. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421508007350 [Accessed October 20, 2014].

Zhivov, A. et al., 2013. Energy performance optimization for Army installations. *Building Services Engineering Research & Technology*, 34(1), pp.87–101. Available at: https://login.libweb.lib.utsa.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=bth&AN=85148612&scope=site.

Zhou, J. & Chen, Y., 2010. A review on applying ventilated double-skin facade to buildings in hot-summer and cold-winter zone in China. *Renewable and Sustainable Energy Reviews*, 14(4), pp.1321–1328. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1364032109002792 [Accessed September 5, 2014].

Zhou, N. et al., 2006. An analysis of the DER adoption climate in Japan using optimization results for prototype buildings with U.S. comparisons. *Energy and Buildings*, 38(12), pp.1423–1433. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778806000843 [Accessed October 21, 2014].

Zhou, N. & Lin, J., 2008. The reality and future scenarios of commercial building energy consumption in China. *Energy and Buildings*, 40(12), pp.2121–2127. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778808001369 [Accessed July 19, 2014].

Zhu, N. et al., 2011. Energy performance and optimal control of air-conditioned buildings with envelopes enhanced by phase change materials. *Energy Conversion and Management*, 52(10), pp.3197–3205. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0196890411001683 [Accessed October 21, 2014].

Zimring, C., 2014. Facility Performance Evaluation (FPE). Available at: https://www.wbdg.org/resources/fpe.php?r=utilize_management [Accessed January 11, 2016].

Zogou, O. & Stapountzis, H., 2011. Energy analysis of an improved concept of integrated PV panels in an office building in central Greece. *Applied Energy*, 88(3), pp.853–866. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261910003405 [Accessed September 30, 2014].

Appendices

Appendix A: Overview of the literature

Article focus	Description	Articles
Organizational/ Management paradigm (74)	These journal articles have focused on energy benchmarking, building energy audits, building energy characterization using mathematical methods, operation management of building components and development of methods to analyze factors affecting building energy.	(Escrivá-Escrivá et al. 2012) (Chung 2012) (Escrivá-Escrivá 2011) (Carlo & Lamberts 2008) (Masuda & Claridge 2014) (Chung et al. 2006) (Martin 2013) (Hall 2014) (Peterman et al. 2012) (Bhandari et al. 2012) (Borgstein & Lamberts 2014) (Melo et al. 2012) (Goyal et al. 2013) (Yu et al. 2014) (Radhi 2009) (Tulsyan et al. 2013) (Hinnells 2008) (O'Donnell et al. 2013) (Altwies & Nemet 2013) (Mohareb & Kennedy 2014) (Bynum et al. 2012) (Azar & Menassa 2014) (Talyor & Miner 2014) (Sun et al. 2010) (Zhu et al. 2011) (Rupp & Ghisi 2014) (Yu & Chan 2012) (N. Wang et al. 2013) (Du et al. 2014) (Saidur et al. 2011) (Yik et al. 2001) (Fong et al. 2006) (Schein et al. 2006) (Li et al. 2013) (Fontanini et al. 2013) (Chua & Chou 2010) (Wagner et al. 2014) (Batista et al. 2011) (Zhou & Lin 2008) (Sabapathy et al. 2010) (Buck & Young 2007) (Yang & Hwang 2007) (Alexandre et al. 2011) (Yu & Chow 2007) (Kamilaris et al. 2014) (Yau & Hasbi 2013) (Chow et al. 2013) (Kneifel 2011) (Ruan et al. 2009) (Yamaguchi et al. 2007) (Bansal & Goel 2000) (Lam & Li 2003) (Sezgen & Koomey 2000) (Melo et al. 2014) (Zhao et al. 2009) (Zhou et al. 2006) (Lam 2000) (Lee et al. 2001) (Lin & Hong 2013) (Yu & Chan 2007) (Mago & Smith 2012) (Lehmann et al. 2007) (Bruno 2011) (L. C. Ng et al. 2013)
Behaviour/ operation paradigm (4)	These articles have focused on topics related to human behavior associated with building energy consumption including regulatory and	(Fasiuddin & Budaiwi 2011) (Lee & Yik 2002) (Janda 2014) (Hsieh et al. 2007)

Article focus	Description	Articles
	voluntary approaches associated with operations.	
Technical paradigm (50)	These articles have focused on various technologies, methods, programs that enable superior building energy performance. Some of these articles have studied the impact of energy retrofits and other external factors on building energy performance.	(Lollini et al. 2010) (Andrews & Krogmann 2009) (Ramana et al. 2014) (Brown et al. 2002) (Susorova et al. 2013) (Borreguero et al. 2014) (P. K. Ng et al. 2013) (Manz & Frank 2005) (Zhou & Chen 2010) (Ibrahim et al. 2014) (Haq et al. 2014) (Ehrlich et al. 2002) (Thomas et al. 2012) (Khan & Abas 2011) (Yan et al. 2014) (Liu et al. 2010) (Huang et al. 2011) (Y. Huang et al. 2013) (Chae et al. 2014) (Chow et al. 2011) (Yu & Chan 2005) (Gvozdenac et al. 2009) (Sanaye et al. 2010) (Li & Wu 2010) (Xu & Qu 2013) (Wang & Song 2012) (Chua et al. 2013) (Lee & Lee 2007) (Wallin et al. 2012) (Maheshwari et al. 2001) (Cavique & Gonçalves-Coelho 2009) (Gagliano et al. 2012) (Yun et al. 2013) (Wang & Song 2013) (Moretti et al. 2014)(Yang & Becerik-Gerber 2014) (Artmann et al. 2008) (Naimaster & Sleiti 2013) (Medrano et al. 2008) (Hussain et al. 2013) (Mann et al. 2006) (Wijayatunga et al. 2006) (Zogou & Stapountzis 2011) (Rezaie et al. 2011) (Yang et al. 2010) (Sarbu & Sebarchievici 2014) (Menassa 2011) (Kircher et al. 2010) (Yu Huang et al. 2013) (Peng et al. 2014) (Zhao et al. 2012) (Vine 2003) (Roberts 2008) (Woo & Menassa 2014) (Picco et al. 2014) (Daly et al. 2014) (Pitts 2008) (Yalcintas & Kaya 2009) (Rankin et al. 2004)

Appendix B: Building operational performance indicators

	Indicator	Reference
I_1	Availability of measures for protection against vandalism and security	(Félio & Lounis 2009)
I_2	User satisfaction level (Through a survey)	(Green Building Council of Australia 2015)
I_3	Indoor air quality (IAQ)	(Namini et al. 2014)(HKGBC 2010)(Canada Green Building Council 2009a)(Green Building Council of Australia 2015) (Green Building Council Denmark n.d.)(Institute for Building Efficiency 2013)(Green Building Initiative 2014) (Canada Green Building Council 2009a)(Canada Green Building Council 2009a)(Institute for Building Efficiency 2013) (Lai & Yik 2009)
I_4	Thermal comfort to the users	(HKGBC 2010)(Green Building Council of Australia 2015)(Green Building Council Denmark n.d.)(Lai & Yik 2009)
I_5	Building cleanliness and visual comfort to the users	(Canada Green Building Council 2009a)(Green Building Council of Australia 2015)(Institute for Building Efficiency 2013)(Institute for Building Efficiency 2013)(Green Building Initiative 2014) (Green Building Council Denmark n.d.)
I_6	Indoor noise level	(Oyedele et al. 2012)(HKGBC 2010) (Kamali & Hewage 2015) (Green Building Council of Australia 2015)(Lai & Yik 2009)
I_7	Indoor luminance level	(Namini et al. 2014) (Canada Green Building Council 2009a)(Green Building Council of Australia 2015)(Institute for Building Efficiency 2013)(Institute for Building Efficiency 2013)(Green Building Initiative 2014)
I_8	Adequacy of building amenities to users (Customizable based on the building type)	(Correia & Wirasinghe 2008)
I_9	Condition rating of building equipment	(Green Building Council Denmark n.d.) (Félio & Lounis 2009) (Institute for Building Efficiency 2013)(Green Building Initiative 2014)

	Indicator	**Reference**
I_{10}	Access to services in normal and emergency conditions	(Félio & Lounis 2009)
I_{11}	Number of deaths and injuries caused by using the public infrastructure (i.e. Number of safety related incidents)	(Félio & Lounis 2009)
I_{12}	Non planned service interruptions as a percentage to planned service interruptions	(Félio & Lounis 2009)(Han et al. 2015)
I_{13}	Number of user days with no service interruptions	(Félio & Lounis 2009)(Han et al. 2015)
I_{14}	Quality of swimming pool water	(Green Building Initiative 2014)
I_{15}	Annual energy use intensity (GJ/m^2)	(Vijayan & Kumar 2005)(Vučićević et al. 2014)(Srinivasan et al. 2014)(El shenawy & Zmeureanu 2013) (HKGBC 2010)(BRE Global 2012)(Green Building Council Denmark n.d.) (Energy star 2015)(Institute for Building Efficiency 2013)
I_{16}	Annual renewable energy consumption (As a proportion of the total energy)	(Namini et al. 2014) (HKGBC 2010)(Canada Green Building Council 2009a)(Green Building Council Denmark n.d.)(Institute for Building Efficiency 2013)(Green Building Initiative 2014)
I_{17}	Annual GHG emission reduction	(Vučićević et al. 2014)(El shenawy & Zmeureanu 2013) (HKGBC 2010)(BRE Global 2012)(Green Building Council of Australia 2015)(Green Building Council Denmark n.d.)(Institute for Building Efficiency 2013)
I_{18}	Annual water consumption per user	(Vijayan & Kumar 2005)(El shenawy & Zmeureanu 2013) (HKGBC 2010)(BRE Global 2012)(Green Building Council Denmark n.d.)
I_{19}	Amount of water recycled as a % to waste water	(HKGBC 2010)(Green Building Council of Australia 2015) (Institute for Building Efficiency 2013)
I_{20}	Average cost of operation as a percentage of annual income	(Green Building Council of Australia 2015)
I_{21}	Amenities for persons with disability	(Namini et al. 2014)(HKGBC 2010)
I_{22}	Cycling convenience for the users	(Green Building Council Denmark n.d.)

Appendix C: LOS indicator benchmark definition

Indicator	**Data Source**	Benchmark	Performance levels				
			Very High	**High**	**Moderate**	**Low**	**Very Low**
I_1	Qualitative / Observation	Municipality defined	State of the art security features are installed (e.g. sensors) , building is continuously monitored and security service is stationed at the facility	building is continuously monitored and security service conducts routine patrols	Security service is contracted and they conduct routine patrols	Building is monitored using CCTV	No security measures are in place
I_2	Through a survey	Municipality defined	Very Satisfied	Satisfied	Neutral	Dissatisfied	Very Dissatisfied
I_3	Measured (mg/m^3)	Literature (Parrat et al. 2012)	0<0.2		0.2-0.3	0.3<	
I_4	Measured (°C)	Municipality defined	25-26		22-24		<22 & >26
I_5	Through a survey	Municipality defined	Excellent	Good	Moderate	Bad	Very bad
I_6	Measured (dB(A))	NRC (Warnock 2001)	>40		40-45	45<	
I_7	Measured (Lumens/Square Meter)	U.S. General Services Administration (U.S. General Services Administration 2016)	>750		500-750	500>	
I_8	Through a survey	Municipality defined	Very Satisfied	Satisfied	Neutral	Dissatisfied	Very Dissatisfied
I_9	Expert judgement	Municipality defined	Excellent	Good	Fair	About to fail	Failed

Indicator	Data Source	Benchmark	Performance levels				
			Very High	High	Moderate	Low	Very Low
I$_{10}$	Expert judgement	Canadian Centre for Occupational Health & Safety, Emergency Planning (Canadian Centre for Occupational Health & Safety 2017)	Emergency preparedness plan is established updated and regular drills are conducted	Emergency preparedness plan is established and regular drills are conducted	Emergency preparedness plan is available	Standard safety and emergency plans are available	No emergency response procedures
I$_{11}$	Daily logs	Municipality defined	0-2	1-3	2-4	3-5	5<
I$_{12}$	Daily logs (Percentage)	Municipality defined	0-2%	1-3%	2-4%	3-5%	5%<
I$_{13}$	Daily logs	Municipality defined	0-2	1-3	2-4	3-5	5<
I$_{14}$	Monitored information	BC Ministry of Health (BC Ministry of Health 2014)	Chemical parameters are maintained in the specified range and no health concerns are reported	Chemical characteristics of pool waster is maintained between following ranges; free chlorine 0.5-5 ppm; chlorine cyanurate 1-5ppm; bromine 1.5-5 ppm; combined chlorine <1ppm; pH 7.2-7.8; total alkalinity 80-120; calcium hardness 180-220;	Chemical parameters slightly deviate from the specified range	Chemical parameters significantly deviate from the specified range	Chemical parameters significantly deviate from the specified range and health problems are reported
I$_{15}$	Monitored information (GJ/m^2)	CIBSE(CIBSE 2001)	<725	725-1573	1149-1997	1573-1997	1785
I$_{16}$	Monitored information (As proportion of total energy)	LEED (Canada Green Building Council 2009b)	>12%	12-7.5%	9-6%	6-3	3%>

Indicator	**Data Source**	Benchmark	Performance levels				
			Very High	**High**	**Moderate**	**Low**	**Very Low**
I$_{17}$	Calculated using energy demand (Percentage of GHG emission reduction from the previous year)	Municipality defined based on climate action plans	>33%	33%-20%	20%-0	0	Increase
I$_{18}$	Monitored information (m^3/user/annum)	CIRIA (Waggett & Arotsky 2006)	<60	60-130	95-175	130-220	220<
I$_{19}$	Monitored information (Percentage of waste water recycled)	LEED (Canada Green Building Council 2009b)	<1%	1-2%	1-3%	2-4%	4%<
I$_{20}$	Calculated data from P&L	Municipality defined	>0		0	0<	
I$_{21}$	Monitored information	United Nations (United Nations 2004)	Standard facilities are available for disabled workers and visitors. Multiple entrances one shower room, one rest room and one changing room per facility are accessible to a wheelchair user. Sports halls and spectator areas are accessible.	Standard facilities are available for disabled workers and visitors. Multiple entrances are available.	Standard amenities are available disabled workers and visitors. Entrance via main entrance	Building can be accessed by a wheel chair user via alternative entrance	Limited amenities are available for disabled.
I$_{22}$	Monitored information	City of Nelson (City of Nelson 2013)	Bicycle parking lockers are available for within 15m of the entrance. Bicycle parking is well lit , visible to visitors and separated from car parking	Bicycle parking is within 15m to the main entrance and separated from car parking.	Bicycle parking is available in a side of the building and is separated from car parking.	Bicycle parking is not separated from car parking available at a side of the building.	No parking facilities for cyclists

Appendix D: Energy simulation results

Component		**Description**	**Investment**	Energy Saving (GJ)	
				Natural Gas	**Electricity**
Building Envelope	R1	Increase the insulation of the roof	119,585	735	0
	R2	Replace front glazing with a double-glazed system.	89,380	768	0
	R3	Increase the insulation of walls to R38	83,248	1270	0
Lighting System	R4	Lighting retrofit to LED	124,000	0	737
	R5	PV electricity for the building	248,300	0	462
	R6	Daylight sensing lighting controls	92,283	0	388
Pool heating	R7	Geothermal pool water heating	178,000	2451	0
Hot water supply	R8	Use of solar preheater	9,000	178	0
	R9	Solar hot water systems	15,000	222	0
Building HVAC system	R10	Solar ventilation preheating	22,000	668	0

Appendix E: Provincial grid and natural gas data

Province	Energy Rate (c/Kwh)(Manitoba Hydro 2015)	Emission Factor (g CO2eq/Kwh)	Energy Rate (CAD/GJ))	Emission Factor (kg CO2eq/GJ) (Ministry of Environment BC 2016)
Newfoundland and Labrador	N/A			
Prince Edward Island	N/A			
Nova Scotia (Environment Canada 2014a; Heritage Gas 2016)	15.38	790	11.65	49.87
New Brunswick (Environment Canada 2014a; Enridge Gas New Brunswick 2016)	12.68	440[5]	6.08	
Quebec (Environment Canada 2014a; Gaz Métro 2016)	9.897	3.4	2.37	
Ontario (Environment Canada 2014a; Union Gas 2016)	15.124	110	4.73	
Manitoba (Environment Canada 2014a; Manitoba Hydro 2016)	8.147	4	9.34	
Saskatchewan (Environment Canada 2014a; SaskEnergy 2016)	12.36	440	4.30	
Alberta (Environment Canada 2014a; ATCO Gas 2016)	11.328	910	1.91	
BC (Environment Canada 2014a; FortisBC 2016)	11.411	9	2.31	
Yukon	N/A			
Territories and Nunavut	N/A			

---

[5] 2011 data