Evaluation of School Buildings Using Sustainability Measures and Life-Cycle Costing Technique

Othman Subhi Daifullah Alshamrani

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By: Othman Subhi D Alshamrani

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Dr. Tarek Zayed

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Dr. Ashutosh Bagchi

______________________________ Thesis Co-Supervisor
Dr. Khaled E. Galal

______________________________ Thesis Co-Supervisor
Dr. Sabah T. Alkass

Approved by______________________________
Dr. Maria Elektorowicz, Graduate Program Director

July 16, 2012______________________________
Dr. Robin A.L. Drew, Dean
Faculty of Engineering & Computer Science

ABSTRACT

Evaluation of School Buildings Using Sustainability Measures and Life-Cycle Costing Technique

Othman Subhi D. Alshamrani, PhD, Concordia University, 2012

Greenhouse gases and energy extraction, production and consumption contribute to polluting the environment, and have led to climate change and global warming, now ranked as one of the top priorities on the United Nations' environment agenda (Montreal & Kyoto protocols). In the United States and Canada, the building sector represents the third-largest domain of total energy consumption, after the industrial and transportation sectors.

In Canada and the United States alone, close to 80 million students, teachers and staff spend at least eight hours a day in schools. There is a growing demand to construct sustainable schools designed to provide more healthy, comfortable and productive learning environments as well as to reduce energy consumption and building costs.

The research presented here details the development of a Selection Framework that enables school boards to select sustainable and cost-effective structure and envelope types for new school buildings. The selection is performed based on an evaluation of the LEED (Leadership in Energy & Environmental Design) rating system and life-cycle costing techniques for typical structure and envelope-type alternatives. Fourteen different structure and envelope types are investigated, covering steel, concrete, and wood structures, in various combinations covering both conventional and sustainable options.

A Sustainability Assessment Model is developed to measure the sustainability performance of conventional or “Non-green” alternatives, based on the evaluation of certain LEED categories such as energy consumption, recyclability and reuse of material, along with incorporating the LCA (Life Cycle Assessment) technique. Furthermore, Life Cycle Costs Forecasting Models are developed by applying Monte Carlo simulation to determine the cost effectiveness or the economic viability for fourteen green and non-green school structure alternatives. Comparisons between these alternatives are performed using various deterministic and stochastic approaches in accordance with confidence levels, and risk assessment using the Efficient Frontier technique.

The selection criteria was evaluated and weighted by experts' opinions. Their evaluation indicates that running costs represent the most significant criterion, followed by initial costs and then sustainability. The selection of alternatives based on a deterministic approach was subjected to high risk, and the selection is also enhanced by applying the Efficient Frontier technique (risk assessment). It is found that, if the selection is based on only one life cycle stage, it would lead to a decision that would not be the best for the long term. Hence, whole life cycle stages should be considered in the selection.

It is seen that this research provides a method that can assist governments and decision makers in minimizing their overall expenditures on public buildings and to provide the best possible structural/envelope system, while simultaneously reducing greenhouse gas emissions and minimizing the environmental impact associated with public sector buildings.

"وقل رب أرحمهما كما ربياني صغيرا"

إهداء إلى والدي الغالي صبحي ضيف الله ووالدتي الغالية رحمة محمد الشمراني

إهداء إلى زوجتي الغالية منى مسفر الشمراني

إهداء إلى أبنائي الأعزاء سلطان وسلمان وعمر وإبنتي الغالية سيرين والتي سوف ترى النور قريبا بإذن الله

إهداء إلى جميع إخواني وأخواتي وذراريهم الأعزاء

To My Parent; Subhi Daifullah and Rahmah Mohammed

To My supportive Wife Mona Masfer Alshamrani

To My Lovely Kids Sultan, Salam, Omar, and new expected baby daughter In Sha ALLAH Sirin

To my precious brothers and sisters and their kids

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List of Nomenclatures and Abbreviations

AHP	Analytical hierarchy process
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
CI	Condition index
CO_2	Carbon dioxide
CSCE	Canadian Society for Civil Engineering
Cα	Cronbach's alpha
MAUT	Multi Attribute Utility Theory
RW	Relative Weight
Wi	Weight
LEED	Leadership in Energy and Environmental Design
$\overline{V}$	Sum of variance of overall points
Vi	Variance of values for each point
N	number of points
LCC	Life Cycle Costs
LCA	Life Cycle Assessment
SS	Conventional steel structure with exterior steel siding walls
SC	Conventional steel structure with exterior concrete brick walls
SW	Conventional steel structure with exterior wood frame walls
WW	Conventional wood structure with exterior wood frame walls
WC	Conventional wood structure with exterior concrete brick walls
CM	Conventional concrete structure with masonry walls (cavity walls)
CC	Conventional precast concrete structure with precast wall panels
GSS	Green steel structure with exterior concrete brick walls
GSC	Green steel structure with exterior wood frame walls
GSW	Green wood structure with exterior wood frame walls
GWW	Green wood structure with exterior wood frame walls
GWC	Green wood structure with exterior concrete brick walls
GCM	Green concrete structure with masonry walls (cavity walls)

GCC	Green precast concrete structure with precast wall panels
H_0	null hypothesis
H_a	Alternative hypothesis
R^2	Coefficient of multiple determinations
R^2 adj	Adjusted coefficient of multiple determinations
IC	Initial Costs
RC	Running Costs which include $(\mathrm{EC} + \mathrm{O\&M} + \mathrm{MRC})$
EC	Energy Costs
O&M	Operating & Maintenance costs
MRC	Major repairs costs
SV	Salvage value
EIC	Environmental Impact costs
i	Discount Rate
j	Inflation Rate
n	Study period
Vi (X)	Total Score Value
Wi	Weight of criteria
Ui	Utility score
WIC	Importance weight of initial costs
UIC	Utility score of initial costs
WRC	Importance weight of running costs
URC	Utility score of running costs
WEIC	Importance weight of environmental impact costs
UEIC	Utility score of environmental impact costs
WSV	Importance weight of salvage values
USV	Utility score of salvage values
WSUS	Importance weight of sustainability
USUS	Utility score of sustainability
ANSI	American National Standards Institute
IESNA	Illuminating Engineering Society of North America
SAM	Sustainability Assessment Model

CR	Consistency Ratio,
RI	Random Consistency Index
CI	Consistency Index .
λ_{max}	Largest eigenvalue
u(x)	Single attribute utility function.
CO2e	Quantified equivalent carbon dioxide
EUAC	Equivalent uniform annual cost
PV, PW	Present Value, Present Worth
NPV	Net Present Value
AW	Annual Worth
SIR	Savings/investments ratio
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
WLCC	Whole Life Cycle Costs
GHG	Green House Gases
UN	United Nations
GWP	Global warming potential
M/R	Major and Repairs Costs
FTMRC	Forecast total maintenance and repair costs
BOMA	Building Owners and Managers Association
USGBC	United States Green Buildings Council
DOE	Department of Energy
ODP	Ozone depletion potential
LSP	Logical Scoring of Preferences
SME	Small and Medium Enterprises
CAD	Canadian Dollar
PDF	Probability distribution function
T	Regression parameter’s coefficient tests
S	Standard Deviation
F	Regression relation test

CHAPTER 1: INTRODUCTION

1.1 Overview

Most school buildings in the United States and Canada were built during three general time periods: the 1920s and 30s, the 1950s and 60s, and the 1980s to the present. In the 1930s, schools were built as a part of government work projects. After World War II, the first baby boom required the number of school buildings to expand from the late 1950s until the early 1970s. School buildings again needed to be built from the late 1980s to the present, due to the second baby boom as baby boomers had children of their own, and since many school buildings had been changed to other uses (Maciha, 2000).

After decades of usage, school buildings often experience substantial maintenance deficiencies, including deterioration of critical building components such as roofs, building envelope, floors, or structural system. Each building material has a certain life span, which is normally influenced by care or lack of maintenance. Minimal or negligent maintenance will cause premature failure, while proper maintenance will yield a long life span. The school's facilities must be clearly identifiable in terms of potential causes of failure and projected life spans. It is significant to realize that the construction year of a school building does not affect or determine the potential for asset failure. The functional age of a school building is determined by the length of time since the latest major renovation or the original date of construction if no major repair has taken place. A school facility should never fail over many years if there is a continuous proper maintenance and commitment to diligence and professionalism (Maciha, 2000).

Energy consumption in the building sector is notably high compared to other sectors such as industry and transportation. For instance, in the U.S., buildings represent 39% of the total primary energy consumption, and in Canada they represent 30%, compared to other sectors (29% for transportation and 41% for industry) (Gov. of Canada, 2009). It is reported that the total energy consumption in Canada increased by 23% (approximately 1592 PJ) over the period 1990-2004. This increase was driven by a 33% increase in activity (a combination of residential and commercial/institutional floor space, the number of households, and industrial production (Gov. of Canada, 2009).

The building industry contributes a high level of pollution because of the energy consumed during the extraction, processing and transportation of raw materials, construction, maintenance, and the demolishing and disposing of buildings. Educational buildings in the U.S. and Canada spend approximately U.S. $16 billion on energy consumption every year. Even though energy costs represent only 2 to 4 percent of the total expenses of school districts, it is one of the several expenditures that can be minimized without negatively influencing the classroom learning environment (Gas, 2009). The US Department of Energy (DOE) calculates that these utility bills could be minimized by 25% if schools are built with the available high-performance design technologies and principles (Plympton, 2004). In a typical school building, space cooling, heating, and lighting together represent approximately 70 percent of total school energy use (Gas, 2009).

The educational buildings sector in Canada is ranked as having the second-highest energy consumption after the residential building sector. This high consumption is mainly due to the current number of establishments and the continuous growth in the number of schools across the country. The educational sector represents 22% of the total energy consumption, followed by the office sector with 13% when all the buildings are evaluated in their different activity sectors, as shown in figure 1.1. The number of educational buildings in Canada is approximately 16,512 buildings with a total floor area of 158,044,023 m^2 and the annual energy consumption is 212,807,311 GJ, as shown in Table 1.1.

Elementary and high schools alone represent approximately 14,587 establishments, which represents 88% of the total educational buildings. The total floor area of these schools is about 113,207,778 m^2 (1,218,558,380 ft^2). The average of energy consumption of these schools is about 1.01 GJ/m^2 (93.8 MJ/ft^2) (NR. of Canada, 2007).

Implementing sustainable, energy-efficient operations and maintenance strategies, and incorporating low-emission equipment into retrofits, school districts may obtain considerable energy cost savings while improving the physical environment of school facilities (Gas, 2009). Hence, the implementation of energy conservation aspects in buildings and in building industry practice will lead to a significant reduction of the environmental impact and reduce life-cycle costs across the building sector.

Table 1.1 Annual Energy Consumption by Activity Sector (N.R. of Canada, 2007)

Sector	Number of Establishments	Energy Consumption (GJ)	Floor Area (M²)	Ener. Intensity (GJ/M²)
Wholesale & Warehousing	45,868	114,162,037	73,462,291	1.55
Retail Trade	97,265	146,861,780	84,568,645	1.74
Information & Cultural Industries	8,429	25,589,044	16,822,634	1.52
Offices	86,531	139,826,874	98,417,673	1.42
Public Administration	6,329	35,305,615	28,927,539	1.22
Education	16,512	212,807,311	158,044,023	1.35
Health Care	47,001	101,035,185	57,596,579	1.75
Accommodation Services	5,887	45,843,413	24,391,987	1.88
Food Services	37,932	42,222,892	13,777,378	3.06
Religious Organization	24,451	50,605,742	46,687,141	1.08
Other	64,658	122,518,056	68,987,813	1.78
Total	440,863	1,036,777,949	671,678,701	1.54

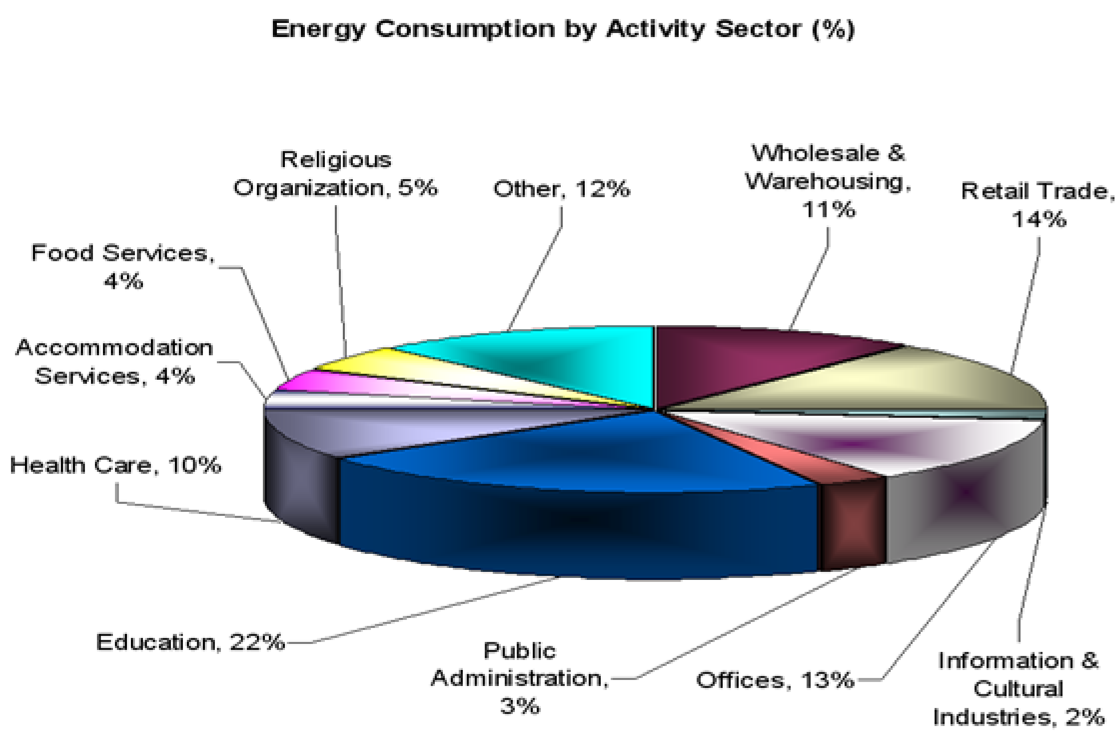


Figure 1.1 Annual energy consumption by activity sector (N.R. of Canada, 2007)

1.2 Problem Statement

The construction of any building's structure and envelope has become easy to achieve, yet the selection of a favorable, most-suitable alternative from sustainability and LCC points of view has become the new challenge. The selection of the structure type or the construction material is often decided based on personal experience or perception, or it could be accomplished by a random untested method that is not evaluated for high performance and sustainability. This research investigates the selection of structure and envelope types based on specific criteria. The first group of criteria is life-cycle costs, including the initial costs, running costs (operating and maintenance costs), environmental impact costs, and salvage values. The second group contains expressions of sustainability principles, such as optimizing energy performance, increasing recyclability and reuse of building components according to LEED standard requirements. This group is then incorporated with overall life-cycle assessment to reduce environmental impacts. Designing school buildings with the objective of meeting the design codes' minimum required performance tends to reduce initial capital costs, yet might deliver schools that are costly in terms of running costs, which does not provide overall cost-effectiveness. As such, the main challenge of this research is to investigate the significance of 'green' cost premium towards adopting better practices in school buildings' construction and the impact of these principles on the overall life-cycle costs (LCC) of facilities built to meet LEED. Life-cycle costs technique is applied to evaluate the economic performance of various structure and envelope types. Furthermore, sustainability concepts are applied to school building design to provide healthy, comfortable and productive learning and working environments. Life cycle components costs and sustainability criteria are evaluated by experts in school boards in North America using relative weights comparison and applying Analytical Hierarch Process (AHP) and Multi Attribute Utility Theory (MAUT).

1.3 Research Objective and Scope

1.3.1 Research Objective

The main objective of this research is to develop a Framework to select the favorable structure and envelope type for school buildings from a cost and sustainability points of view throughout their life cycle.

1.3.2 Scope of the study:

In order to reach the aforementioned research objective, the scope of the study is to:

1- Develop LCC Forecasting Models to compare the performance of conventional and sustainable school buildings.
2- Measure the sustainability level for various structure and envelope types, taking into consideration: energy consumption, recyclability, and life-cycle assessment.
3- Develop a correlation between sustainability, structure and envelope types, and LCC.

4- Develop a decision support system to assist schools boards in their selection of new school buildings during the feasibility analysis stage based on sustainability and the life-cycle costing technique.

1.4 Research Methodology

A systematic and multi-phase methodology is applied to develop a selection framework for conventional and sustainable structure and exposure types, to achieve high performance in LCC and sustainability for new school buildings. Selection criteria were evaluated by experts and got relative importance weights using analytical hierarchy process AHP. These criteria include: initial costs, running costs, environmental impact costs, salvage values, and sustainability principles. The utility preference values for each criterion were also determined by experts using Multi attribute utility theory. In this research, fourteen different structure and envelope types are investigated on building conventional and sustainable schools: steel, concrete, and wood, in various combinations. Each alternative was tested and its performance was measured in the whole selection criteria. Selection framework was developed based on sustainability assessment model (SAM), LCC forecasting models, and risk assessment. SAM consists of several measures include; energy performance, recyclability and reuse of material, and life cycle assessment. LCC forecasting models were developed using deterministic approach and stochastic approach which was investigated at various confidence levels; 95%, 70%, and 50% (median) percentile confidence level. Obtained score by each alternative was estimated by multiplying the obtained utility score by the weight of criterion. This process was repeated for the whole criteria and the total obtained scores were calculated accordingly. Finally, the risk assessment is performed using Efficient Frontier technique to enhance the selection of the most attractive alternative for decision makers.

1.5 Research Organization

Figure 1.2 displays the methodology of the conducted research. The research organization can be described as follows:

Chapter 2 introduces fundamental knowledge related to life-cycle costing and sustainability and presents a literature review of the principle research works that have been conducted in both fields and are relevant to this research.

Chapter 3 introduces the applied methodology for data collection, the analysis process and different techniques and tools which were applied to test the various alternatives. It also explains the applied methodology to develop the framework.

Chapter 4 presents data collection and introduces the methods, techniques, and tools that were used to gather data. It also displays samples of the gathered data.

Chapter 5 presents the developed sustainability assessment model (SAM). It also displays the data analysis of energy simulation, recyclability and reuse, and LCA. The results of the SAM were discussed in details in this chapter as well.

Chapter 6 introduces data analysis such as questionnaires, initial costs, energy costs, and environmental impacts costs, etc. It also discusses the development of regression models, LCC forecasting models, and selection framework.

Chapter 7 presents the implementation of the developed models through applying them on case study. It also displays the whole results with comparing of deterministic and stochastic approaches. It also presents the selection of attractive alternative through the implementation of risk assessment.

Chapter 8 displays the research's conclusions, contributions and limitations, as well as suggestions for enhancement and for future work.

1.6 Research Publications

Several journal and conferences papers were published out of the conducted research work such as:

[J1] *Evaluation of School Structure and Envelope Materials Using Integration of LCA & LEED*, The Facade Tectonics Journal , published by University of Southern California, Los Angeles, California, USA, JUNE 29th, 2012.

[C1] *Energy Consumption Reduction Using Sustainable Building Envelopes' Material in School Buildings*, 3rd International/9th Construction Specialty Conferencele 3è Congrès international et 9e Congrès spécial du génie de la construction Ottawa, Ontario, June 14-17, 2011.

[C2] *Evaluation of School Buildings Using Sustainability Measures and the Life-Cycle Costing Technique.*

[C3] *Incorporating LCA into the LEED Evaluation of Structures and Building Envelopes*, the International Conference on Sustainable Systems and the Environment, American University of Sharjah, UAE, March 23-24, 2011.

[C4] *Use of LEED and LCC Techniques in Evaluation of School Buildings.*

[C5] *Incorporating LCA into LEED in Evaluation of School Buildings,* 4th Canadian Forum on the Life Cycle, Management of Products and Services - cycle2010, May 4-5, 2010.

[C6] *Energy Consumption Reduction In School Buildings in Kingdom of Saudi Arabia,* International Engineering Conference on Hot Arid Regions (IECHAR 2010)Al-Ahsa, KSA, March 1, 2010.

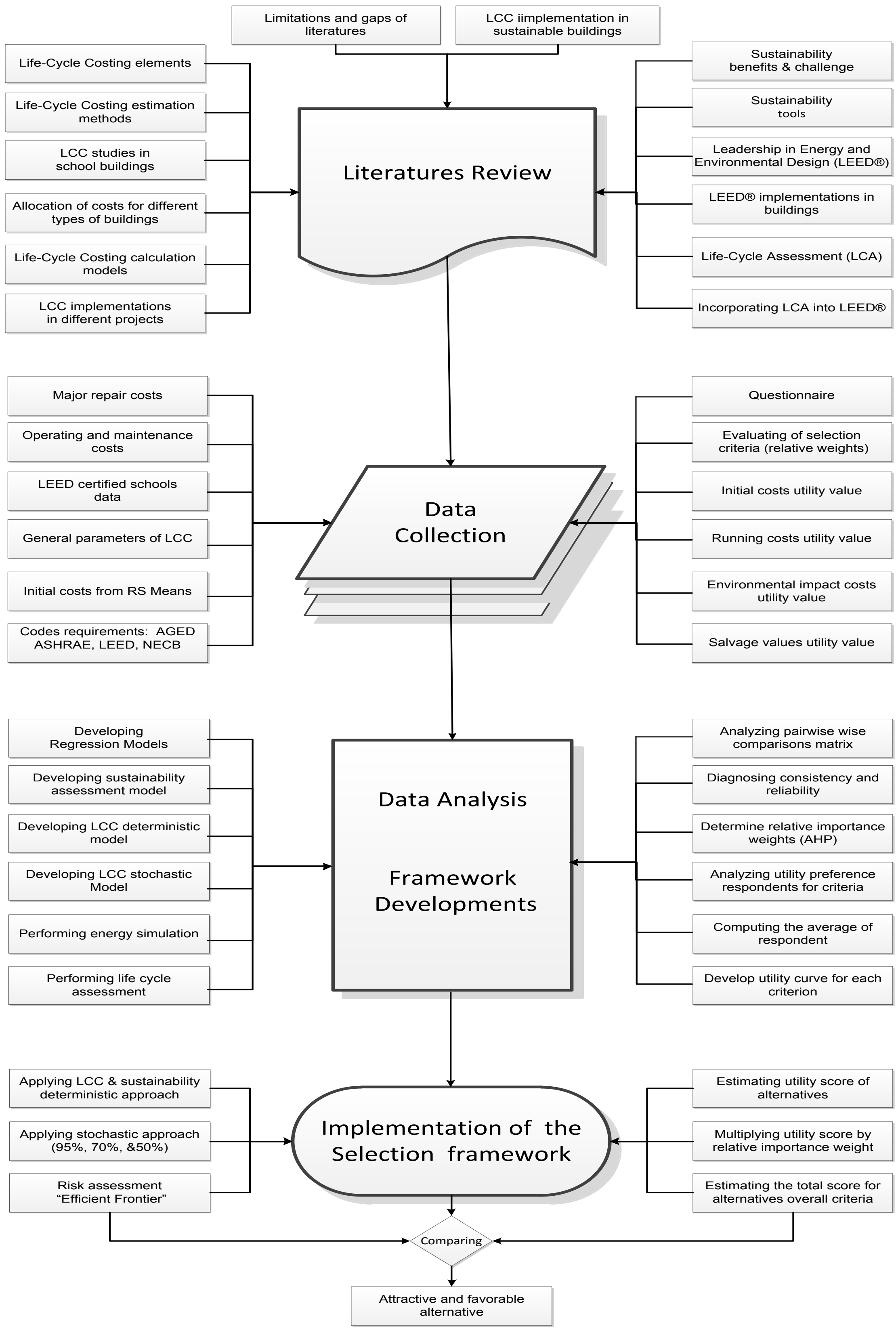


Figure 1.2 Research Methodology

CHAPTER 2: LITERATURE REVIEW

2.1 General

This chapter presents fundamental knowledge related to life-cycle costing and sustainability and presents the major studies that have been conducted in both fields which are related to the proposed research.

2.2 Life-Cycle Costing

Life-Cycle Costing (LCC) is a tool or technique that used to measure the economics of alternative projects that have different parameter values as to their cash flows over a project's total life span (ASTM, 2003). "*Life Cycle Cost is an essential design process for controlling the initial and the future cost of building ownership*" (Tim, 1999). The LCC method is used, for the most part, to determine the lowest results or the most cost-effective choice among several alternatives. It can also show that savings could be realised when the higher initial cost of a building reduces long-term future costs such as: maintenance, operation, and repair or replacement costs. In contrast, a lower initial cost will probably lead to an increase in the running costs and cancel out the initial savings along the project's life span. In the case of constructing a building that has both a lower initial cost and lower running costs compared to an alternative, LCC analysis is not required to prove that it is the most economically viable choice (ASTM, 2005). The essential objective of life-cycle costing is to evaluate possible alternatives for a given project. For example, a choice might be available for constructing roofs project. There are other important factors than the initial capital cost that would have significant contribution to the overall cost throughout the life cycle of the project, such as the operating, maintenance and repair costs, thermal insulation properties and how they will affect heating and cooling, appearance and life expectancy. Life-cycle costing is thus a combination of judgments, predictions and calculations (Ashworth, 1994).

LCC technique provides an evaluation method to measure the economic viability of various proposed options, which can be resulted in measurable scale for the evaluated alternatives. LCC is applied to determine the attractive alternative overall the life cycle stages. The LCC technique can be applied in budget planning, cost control, project feasibility study, preliminary design, and assets or products assessments (Zhang, 1999).

2.2.1 Life-Cycle Costing Elements

One of the definitions of LCC states that all "Significant costs of ownership'' should be involved (Kirk 1995). Figure 2.1 demonstrates the cost types that should be considered in an LCC study by the owners or designers. As can be seen, the Initial Costs contain the total ownership costs related to the initial development of a project (Dell'Isola 2003). Some of these costs include construction costs, fee costs, and other costs such as real estate, site, and professional services, etc. Financing costs consists of the costs of every debt related to the facility's initial cost, such as loan fees, interest and one-time finance charges. The category of maintenance costs includes the ordinary repair and custodial care, annual maintenance contracts, and the wages of facility personnel performing maintenance tasks (Kirk 1995). Operation and energy costs include the utility costs such as fuel and electricity consumption costs and the salaries of the personnel needed to run the facility (Dell'Isola 2003).

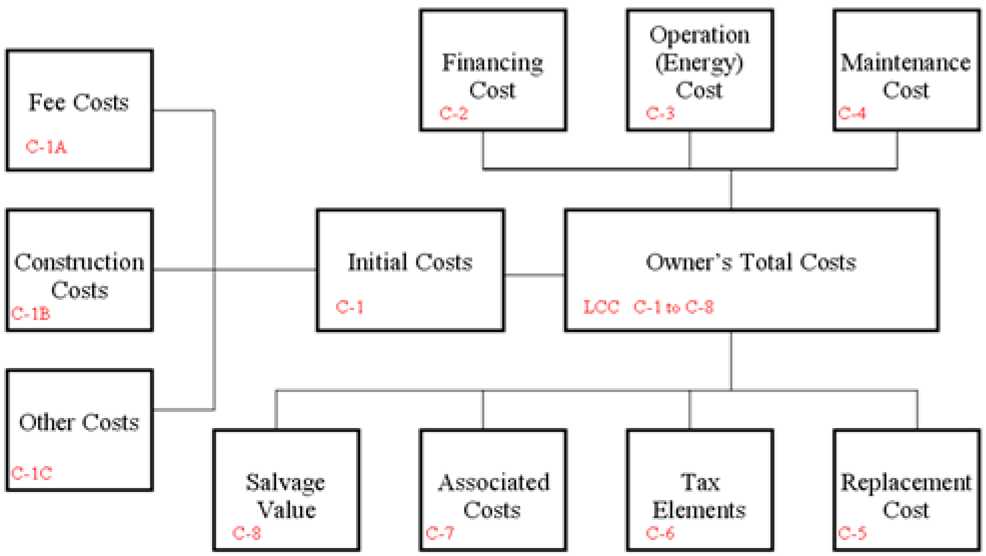


Figure 2.1 Life Cycle Cost Elements (Dell'Isola, 2003)

Operation and maintenance costs can be provided by the owners or could be obtained from published database, and obtained from the manufacturers (Haviland 1978). Energy efficiency studies should be performed by designers to forecast utility and fuel costs. Dell'Isola mentions that "Replacement cost is a one-time cost to be incurred in the future in order to maintain the original function of facility or item". Assignable costs associated with depreciation, taxes, and credits have to be continually adjusted according to changing tax laws (Kirk, 1995). The salvage value of the facility is defined as the value that can be recovered at the end of the study period. This value can be obtained from the standard estimating sources: manufacturers, industry associations, owners experience (Haviland, 1978). The meaning of the associated costs may include all of the other identifiable costs not mentioned previously, such as insurance and security costs (Dell'Isola, 2003).

2.2.2 Life-Cycle Costing Estimation Methods

Life Cycle Cost is the sum discounted dollar cost of owning, running (maintaining & operating), and demolishing a building or a building system over a specific period of time. According to this definition, the LCC equation can be broken down into the following four variables: 1) The relevant costs of ownership: initial cost, running cost (either operating or maintenance cost), and replacement cost; 2)The future income, such as annual income from rent or the salvage value of building at the end of the study period.; 3) The period of time over which these costs are incurred (30, 40, or 50 years); and 4) The discount rate (inflation or deflation rate) that should be applied to the future costs to adjust them with current costs (Tim, 1999).

The LCC is a mathematical technique that utilizes fundamental economic evaluation approaches, such as the annual worth method, the net present value method, and the Savings/Investments ratio (SIR) Method to evaluate the various cash flows of Life-Cycle Cost for different projects.

2.2.2.1 Annual Worth Method

The annual worth (AW) method converts all the cash flows into an equivalent uniform annual series of cash flows over the certain planning horizon. (Alkass, 2007). When this method is utilized, both future costs and present costs will be converted into a uniform annual worth, while taking into consideration the monetary value of time at a particular interest rate (Liu, 2006). All future and present costs will be broken down into equivalent annual payments over all of the life cycle. All equivalent annual costs will then be combined to determine the total uniform annual cost. When various alternatives are compared, the same choice will be made regardless of whether the present worth method or the annual worth method is utilized. The same relative advantages will result from either method of calculation (Liu 2006). The explanation of this AW method can be expressed mathematically as follows:

AW = AW (Annual Income) + AW (Salvage Value) – AW (Initial Cost) – AW (Operating and Maintenance Cost) – AW (Financial Cost) (2.1)

2.2.2.2 Net Present Value Method

The net present value (NPV) method is utilized to convert all cash flows to a single sum equivalent at the starting point of the analysis period (Alkass, 2007). By using this method, all expenditures and income, regardless of occurrence time, will be compared throughout a certain common year, identified as a baseline year. Expenditures and future income will be appropriately discounted to adjust their time value. When these future expenditures are discounted, they will be compared to those incurred “today”, or throughout the “baseline year”. When this discounting occurs, all costs and income are weighed on a common basis and added together to determine the total net present value (Liu, 2006). Since most initial costs occur almost at the same time, initial costs are considered to occur during the base year of the study period. Therefore, there will be no requirement to calculate the present worth of these initial costs because their present worth will be equivalent to their actual cost (Mearig, 1999). The explanation of this NPV method can be expressed mathematically as follows:

NPV = PV (Annual income) + PV (Salvage Value) – PV (Initial Cost) – PV (Operating & Maintenance Cost) – PV (Financial Cost) (2.2)

2.2.2.3 Savings/Investments Ratio (SIR) Method

The savings/investments ratio (SIR) method uses a convenient index which measures the economic performance efficiency of buildings (Zhang, 1999). This method determines the ratio of the present worth of savings to the present worth of net positive cash flows divided by the present worth of net negative cash flows, so for a project to be preferred, the ratio must be greater than one, which indicates that the project is worthwhile (Liu, 2006). The explanation of the SIR method can be expressed mathematically as follows:

SIR = PV savings/ PV investment ratio for investment Where: **(2.3)**

SIR = the saving/ investment ratio for investment

PV (Savings) = the present worth of net positives cash flows

PV (Investment) = the present worth of net negative cash flows

2.2.3 Allocation of Costs for Different Types of Buildings

Rather than considering just the initial cost, the significance of considering LCC is very clear in figure 2.2 Initial costs as well as running costs, such as energy, maintenance, security, and cleaning costs are taken into account. LCC allocation differs from building to building according to their types and functions (Flangan 1989). For example, the initial cost of an office building is considered as the largest single cost. It represents 42% of the LCC and 58% of the running or future costs (cleaning, 20%; other rates such as water, 16%; energy, 10%; annual maintenance, 7%; other maintenance, 5%) (Flangan,1989). In contrast, the initial cost of a typical hospital represents only 6%, while the running costs: maintenance and contracted cost, 12%; fuel and utilities, 6%; drugs and pharmaceutical, 5%; medical supplies and food, 7% represent 30% (Delllsola 2003). When the staffing costs are included in a hospital, they will represent the largest cost which is almost 64% of total life cycle cost.

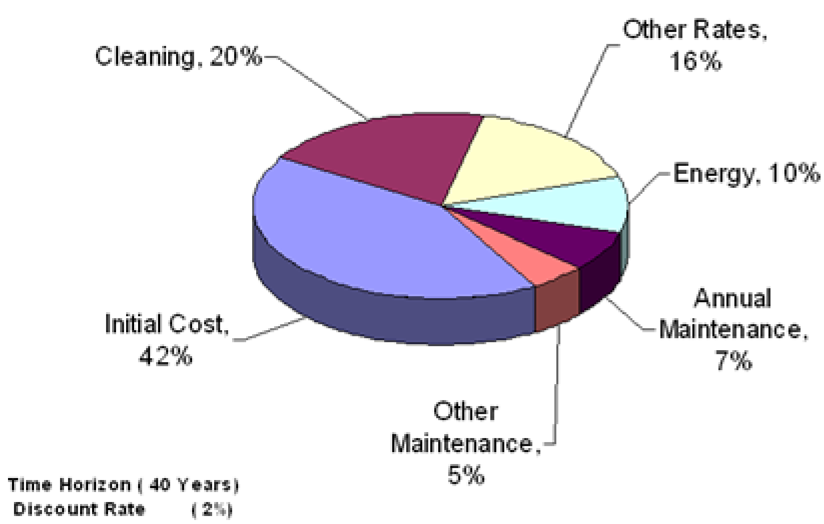


Figure 2.2 Life-Cycle Cost Percentages for an Office Building (Flangan, 1989)

For residential buildings such as nursing homes, the running costs represent almost 60% of the LCC, while the initial cost represents 40% (Flangan, 1989). Therefore, LCC professionals should build up computing models to suit each type of building cost-allocation condition.

The operational stage of a commercial building is significantly longer than the design and construction phase of a project. The design and construction phase is about five to ten percent while the lifecycle cost of the operational life of a building is about 60 to 85 percent of the total lifecycle cost. Acquisition, disposal and renewal costs are between 5.0 and 35 percent of the total life cycle cost (Christian and Pandeya 1997).

2.2.4 LCC Calculation Models

LCC calculation models enable asset stakeholders to predict the cost of obtaining, owning, maintaining, operating, and disposing of their assets. There are three approaches for modeling LCC calculations:

2.2.4.1 The deterministic calculation model

This approach is straightforward, requiring some data such as the discount rate, study period and annual cost prediction estimates for competing alternatives (Boussabaine, 2004). The deterministic approach calculates the net present value of the proposed investment from the study period's series of cash flows utilizing the specified discount rate. The discount rate could be nominal or real, based on stakeholders' requirements. In this approach, all of the LCC terms are calculated utilizing one single value. Sensitivity analysis can be performed for the results if modifying any of the input parameters to observe LCC variation

(Boussabaine, 2004). The LCC deterministic calculation model utilizes the following generic formula:

$$LCC(presen\,tvalue) = C_p(inatial\,\cos t) + \sum_{t=0}^{n} \frac{\mathrm{C_t}\ \text{(sum of relevant LCC)}}{(1+d\ (dicount\ rate))^t} \qquad (3.4)$$

where n= number of years of the period study,

2.2.4.2 The stochastic calculation model

In this approach, LCC could be assumed to be a probability distribution instead of a deterministic value. This distribution could result from the variance as well as from the expected value (Boussabaine, 2004). The LCC cost centers, study period, and discount rate are assumed to be randomly distributed according to one form of probability distribution, such as normal distribution. This model requires that the cash flow for each year of a study period is expressed as uncertain cash flow profiles or as probability distributed functions (Boussabaine, 2004). It also requires treating each cost center element stochastically. The total LCC could be simulated utilizing the following formula in the case when the cash flow profile or the probability distribution function of each LCC discount parameter and cost center is known.

$$f(PV) = f(C_p) + \sum_{t=0}^{n} \frac{f(\mathrm{C_{ti}})}{(1+f(d))^t} \qquad (3.5)$$

2.2.4.3 The fuzzy calculation model

In this model, human judgment is considered in all of the LCC aspects. Fuzzy set theory is considered to be a significant tool for uncertainty modeling, or imprecision emerging from expert perception and opinion. Hence, a rational method in the direction of LCC modeling is to take processes and human subjectivity into consideration. Present value parameters and LCC are usually calculated utilizing statistical techniques and expert judgment. Calculation of present values based on fuzzy numbers could determine the complexities in computing the attributes of LCC and present values (Boussabaine 2004).

2.2.5 LCC Implementations

The LCC technique has been implemented in many research efforts and engineering applications. Its implementation has quite a broad range, as discovered in the literature review. This implementation of LCC is utilized in many fields, such as construction projects, infrastructures, buildings, facilities management.

2.2.5.1 LCC Implementations in Construction Projects

Al-busaad (1997), presented a research to assess the challenges of applying of LCC on construction projects in Saudi Arabia. This research focuses in finding the barriers and the common problems that govern the implementation of this technique on public and government projects. Twenty six major problems are identified and classified into five major groups: unfamiliarity problems, data problems, procedure problems, management problems, and cost problems.

A survey of 45 government agencies and 250 consulting firms concluded that the main reason for not applying LCC application was due to client and management pressure to meet deadlines for design approval and budget design limits. It was agreed upon by both government agencies and consultants that the lack of material resources and un-familiarisation with LCC benefits are other causes for not applying LCC more extensively (Assaf, 2002).

Ferry and Flanagan, in their research “Life Cycle Costing - A Radical Approach” (1991), recommended breaking down the project lifetime for LCC analysis into eleven stages. By using this method, it will be easier for researchers to concentrate on one significant part that has less uncertainty in the study. Significant changes and continuations are revealed from the 1970’s to the 1990’s in LCC technique implementations (Ferry, 1991) As can be seen in Figure 2.3.

Figure 2.3 LCC Implementation using Project Life Stages (Ferry, 1991)

2.2.5.2 LCC Implementations in Infrastructures

Salem et al. (2003) introduced a new method for life-cycle cost computing and evaluating construction and infrastructure rehabilitation alternatives. This approach is derived from simulation application and probability theory. He developed a risk-based LCC model that provides extra information about the levels of uncertainty that accompany the computed LCC. It also takes into account the time to failure of each alternative for pavement construction and rehabilitation. In addition, this research illustrates the different elements of the developed model, the factors influencing service life and pavement performance, and the data input simulation and modeling used for the analysis.

El-Diraby and Rasic (2004) introduced a framework to manage the life-cycle cost of smart infrastructure systems. The framework consists of a model for assessing the life-cycle cost of civil infrastructure systems prepared with smart materials (sensor-embedded materials and fibre-reinforced concrete). It could also consist of intelligent devices (smart signals and smart valves). The model identifies the basic cost components that should be taken into account when evaluating life-cycle costs. Furthermore, the model identifies managerial and design factors that affect these costs values.

Zayed et al. (2002) introduced research that utilized Life-cycle costing to evaluate and compare strategies of various alternatives for paint systems for a steel bridge. Equivalent uniform annual cost (EUAC) and present value (PV) equivalent were applied to evaluate the economic effectiveness and to compare several steel bridge paint systems and different rehabilitation scenario alternatives. Life-cycle cost analysis calculations proved that the three-coat paint system is superior to the others. It was found out that spot repairs every 15 years of paint life was the best for both a maintenance plan based on life-cycle cost analysis as well as the for scenario for three-cost system rehabilitation.

Shahata (2006) developed a stochastic LCC modeling approach for water mains. Several rehabilitation methods were identified: repair, renovation, and replacement. The Monte Carlo simulation approach was utilized to compare the current new installation and rehabilitation methods. The optimal scenario was accommodated for various types of water mains (cast iron, ductile iron, concrete, PVC, and asbestos). Results showed that “slip lining” and “open trench” are the best methods for the renovation and repair categories, respectively. The best method for replacement was open cut for large pipe diameter and pipe bursting for smaller

2.2.5.3 LCC Implementations in Buildings

Khanduri et al. (1996) introduced a model to assess office building life cycle cost at the preliminary design stage. This research was a development of a quantitative life cycle costing model for financial feasibility assessment at the preliminary design stage for office building projects. Three assessment methods are computed in that study: savings/investment ratio, present worth, and annual worth. The developed model contained the majority of the financial factors and technical data that are required to test the economic feasibility for the specified building. It also facilitates calculating the LCC by using minimum and basic input.

Christian et al. (1998) examined the impact of quality on the life cycle costs of barrack blocks at the Canadian Forces base, Combat Training Centre (CTC) Gagetown. The study is conducted to determine the life cycle costs of the 19 existing barrack blocks at CTC Gagetown. The objective of study is to compare building life cycle costs and account for differences to attempt to measure the impact of quality on the life cycle costs of the buildings. The costs were found to be almost the same for buildings with similar levels of maintenance and identical construction. It was hard to objectively determine the impact that quality has had on life cycle costs as there were no barracks that could be considered to be mid-life.

Zhang (1999) designed a quick and economical computing model for office building development, investment, management and assessment decision-making at the preliminary stage. In his thesis a computing model entitled Office_LCC98 was developed to assist practitioners in the real estate profession to make better decisions. This investigation determined the economical rental rates of office buildings, and observed that there was a lack of replacement costs in the database.

Jrade (2004) introduced a methodology that can be utilized for an integrated life-cycle costing system and conceptual cost estimating for building projects. This methodology explains the implementation and development of a system that automates the preparation of conceptual cost estimates and predicts the running costs of building projects. This methodology is applied by combining virtual reality environment (VRE) and computer integrated construction (CIC). Any adjustment in building design drawing can be virtually animated and visualized and will cause modification, resulting in a new conceptual estimate. When initial costs are computed, the maintenance and operating costs for new building will be forecast during its expected life span.

Liu (2006) developed a model to forecast and evaluate maintenance and repair costs for office buildings. The developed forecasting model takes into account the weight of factors that significantly affect maintenance and repair (M/R) costs and the related adjusting factors of these costs. Six main factors affecting M/R costs were identified: ownership, location, city, age, size, and height, and their associated elements defined. Historical data published by the BOMA was adapted, analyzed, and simulated to establish the probability distribution of M/R costs. A prototype FTMRC (forecast total maintenance and repair costs) system and software were developed to apply the developed forecasting model. The FTMRC system provides an analysis of the net present value of M/R and a sensitivity analysis to determine the parameters that affect the NPV of M/R costs. The system also offers both graphical and numerical reports.

Haddad (2008) introduced a model to measure the environmental impacts of building materials in monetary values. The environmental impact is measured in tonnes in the equivalent carbon dioxide, utilizing a life-cycle assessment tool according to the global warming potential (GWP-100). The quantified equivalent carbon dioxide (CO_2e) is then converted into a monetary value to be utilized in the LCC calculation of the environmental impact. The economic LCC of building materials is computed based on ASTM’s standard technique. The monetary value of CO_2 emission is obtained from the stock market, which conforms to the Kyoto protocol's principle of emission trading. "EconoEnviroTLCC Tool" is a web-based design support tool that enables users to calculate the LCC to evaluate and choose the most sustainable building materials.

2.2.5.4 LCC Implementations in Facilities Management

Life-cycle costing assists building designers and owners to make trade-offs between a building's initial and running costs. Life-cycle costing has proven to be the only method to forecast the true cost of basic purchase decisions (Fretty, 2003). Maintenance costs can be drastically reduced by utilizing LCC. To make a positive difference with life-cycle cost analysis, it is very important that the maintenance costs should be applied accurately and that they are up-dated, along with performance information (Fretty 2003).

The specifications and benefits of outsourcing data storage and retrieval are discussed by Vangen (2011) from the facility management and construction aspects of building's life cycles. Inefficiencies in the maintenance and construction of buildings occur due to the lack of integrated infrastructure technology in corporate real estate. These inefficiencies lead to firms losing hundreds of millions of dollars annually.

Bakis et al. (2003) presented a computer-integrated environment that seeks to overcome some usual LCC barriers (shortage of LCC data and complexity of technique). A framework/mechanism was provided for gathering and storing LCC data and a number of tools for supporting and simplifying the application of the technique were developed. The main characteristic of the environment was that it provides a comprehensive approach to LCC by integrating data gathering management of a building and LCC-aware design into a single framework. An interactive and integrated design tool was utilized to assist in and to facilitate the LCC-aware design of buildings. A three-dimensional visualization tool was utilized to aid the facilities manager in the LCC-aware management of buildings.

2.2.6 LCC Studies Related to School Buildings

Many studies have been conducted in the field of life-cycle costing in the building industry but only few that have been performed on school buildings. Few reported studies show the LCC distribution for primary and secondary schools for different life spans and discount rates, with obvious variety in the values for the cost centers but no further information or details have been reported, (see Figures 2.4 & 2.5)

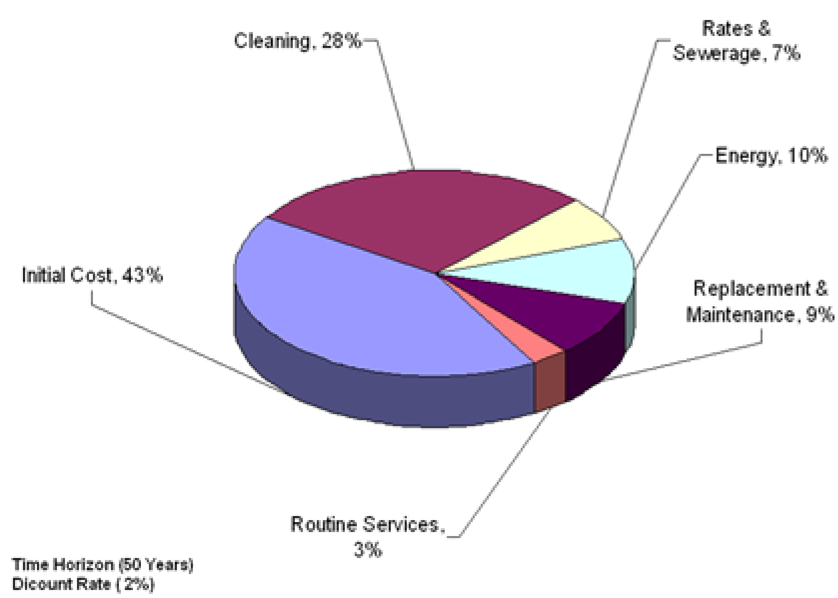


Figure 2.4 Life-Cycle Cost Percentages for A Primary School (Flangan, 1983)

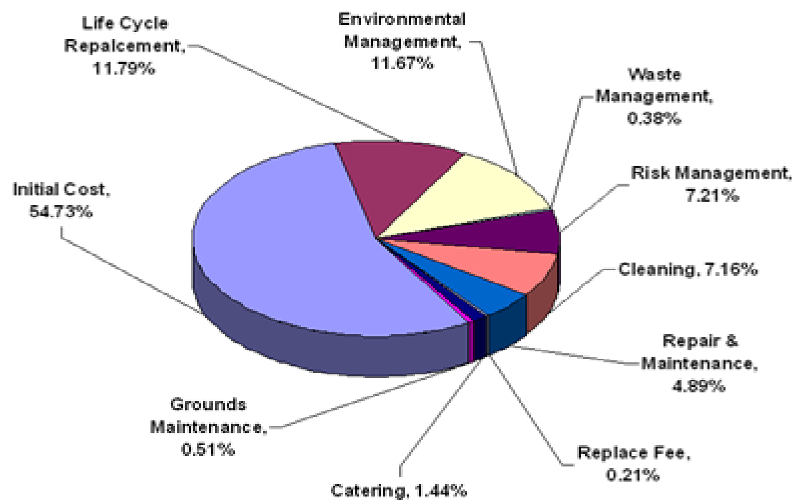


Figure 2.5 Life-Cycle Cost Percentages for a Secondary School (Delllsola, 2003)

Moussatche and Languell (2001) introduced their research on floor materials life-costing for educational facilities. Their study compares interior floor materials that were affordable for use in K-12 educational facilities in the State of Florida at the time of research. Their study shows that, in addition to limited time and resources to properly assess the LCC of building materials, difficulties are due to the tight schedule of developing, designing, and managing educational facilities. They also proved that the selection of interior finishing materials is usually governed exclusively by capital cost (Moussatche and Languell, 2001). The flooring alternatives (Exposed concrete, ceramic tiles, terrazzo, laminated wood, etc.) are compared utilizing LCC analysis based on service life of 50 years, as determined by the Florida Department of Education. Initial costs, operational and maintenance (O&M) costs, and replacement costs for each alternative are computed to compare the materials according to the net present worth (NPW) method. The results show that all of the low initial cost alternatives will not necessary have a high LCC, and vice versa. Their research findings did not show the presence of a correlation between LCC and the initial cost of the flooring alternatives. Correlations are noted between increasing O&M costs and a decreasing service life and to an increasing corresponding NPV.

Fretwell (1984) conducted research in designing a system based on life-cycle costing for educational buildings in Alabama. The study focused on a particular and limited architectural use of life-cycle costing, not as a macroeconomic technique, but as a medium for a cost control dialogue between educational administrators and architects while selecting components and systems for proposed educational buildings. A 40-year life was assumed in this study. A computer program for performing a life-cycle cost analysis at the design level was developed using features and concepts that were discovered during the research stage. The computer program was applied on a high school building prototype that was designed as a part of this study to reflect a typical educational facility in Alabama. Energy consumption and building cost values were generated from the computer program runs. Nine different building design modifications were analyzed in the program to demonstrate the energy and cost consequences of different design concepts. Energy consumption was calculated by making some changes in the variables, including skylights, shading devices, windows and other variables. “The resulting energy usage varied by as much as 36%. Random changes in building materials and finishes resulted in initial building cost changes ranging from $5,000 to nearly $50,000 (at time of the study)

2.3 Sustainability

2.3.1 Overview

The planet is currently suffering from many environmental problems. The level of these environmental issues extends from local to regional to global. By using non-environmentally sound or unsustainable development, the boomed construction, rapid industrialization, urbanization, and other developments in technologies have caused air and water pollution and have contaminated soil quality to the extent that it interferes with the basic needs of society (Sonnemann, 2004). Environmental problems such as ozone depletion, acid rain, and global warming are increasing significantly over the last few years, a situation that requires the awareness and attention of governments and societies (Harris, 1999).

Local climate change and global warming are now ranked as one of the top priorities on the United Nations' environment agenda such as Montreal & Kyoto protocols. The Kyoto Protocol is an international agreement linked to the "United Nations Framework Convention on Climate Change". The main feature of the Protocol is that it sets binding targets for about 37 industrialized countries including Canada and the European community for minimizing greenhouse gas (GHG) emissions by 5% against 1990 levels over the five-year period 2008-2012 (UN, 2011).

Abundant benefits can be provided by buildings to their occupants, but they can be major contributors to the adverse impact on the surrounding environment. Literature review shows that 1.8 million residential buildings are built every year in the United States (U.S. EPA 2004). There are 220,000 residential buildings constructed yearly in Canada (Canada Statistics 2009). This boom in building construction generates many inputs and outputs to the environment during the life-cycle of buildings. For example, different natural resources are consumed during the construction process, such as water, energy resources, land, and minerals. Furthermore, many types of contaminants are released back to the environment. These environmental inputs and outputs cause serious environmental issues including ozone depletion, air and water pollution, waste disposal, and global climate change. All of these environmental impacts result in damage to human health, natural resources, and biodiversity (Li, 2006).

Approximately 73 million U.S. citizens (68.5 million students) attend 117,007 private and public secondary, middle and primary schools (U.S. EPA 2004). In addition, there are about 7 million students and teachers daily spend at least eight hours of their time in Canadian schools (G. of Canada 2009). These schools are often unhealthy and somewhat polluted, which affect student's productivity and ability to learn (Kats, 2006). Conventional schools are usually designed to barely meet the minimum building code requirements, which are usually do not aim for sustainable performance, they aim for guaranteeing the structural performance for a limited number of years (50 years for buildings, and 75 years for bridges). Designing schools with the intent of meeting the lowest code requirements tends to reduce initial capital costs but delivers schools that are costly in terms of running costs (operating and maintenance costs) (Kats, 2006). One attempt to meet the recent growing demand to overcome this problem is constructing green schools that aim to provide healthy, comfortable and productive learning and working environments as well as to reduce the energy consumption and building cost. These green schools have high performance ratings, and generally cost more to build, which is considered as one of the major barriers from two points: an expanding student population and limited school budgets (Kats, 2006).

2.3.2 Sustainable Buildings

Sonnemann et al. (2004) mentioned that “Sustainable development is understood as satisfying the needs of the present generation without compromising the needs of the future generations”. Three main aspects, economic, environmental, and social, are taken into account by this sustainability outlook. It is necessary to be aware of the effects of modern day practice on the environment in order to fully comprehend the importance of sustainability.

A green or a sustainable building is the result of a philosophy in design that aims to maximize the efficiency of resource usage, such as water, energy, and materials. In addition, it focuses on minimizing a building’s impact on the environment and on human health throughout the building's lifecycle, through better siting, design, construction, maintenance, operation and demolition (William, 2005). Though the concept of sustainable building is interpreted in many various ways, the ‘ordinary’ view is that buildings should be designed and operated to minimize the overall impact of the built environment on human health and the surrounding environment by:

- efficiently using water, energy, materials and other resources;
- improving employee productivity;
- protecting users health; and
- reducing waste, pollution and environmental degradation (USEPA 2009).

The concept of sustainable development is rapidly becoming recognised and sought after worldwide. The construction of sustainable buildings has increased significantly thanks to many factors, such as the need for energy conservation, economic pressures, and the demand to minimize the negative impact of building's construction and operation on the environment. The construction of sustainable buildings proved to have more challenges and has led to the utilization of innovative construction methods (Attalla and Yousefi, 2009). There is increasing recognition of the significance of implementing the principles of sustainability in construction. The significant cause for this recognition is the concern that the world must act responsibly and urgently to the damage in the environment caused by human activities. Many governments recognize this concern and have signed up to agreements committing major improvements in a short time. Some commercial organizations such as building contractors and others in the manufacturing industry have also recognized that there are business advantages in implementing sustainable principles in their operations (Attalla and Yousefi, 2009).

2.3.2.1 Benefits of Implementing Sustainability

Many benefits can be gained from utilizing sustainability and green development in terms of the main aspects: social, economic, and environmental.

1. **Health and Community Benefits:**

- Improving thermal, air, and acoustic environments;
- Enhancing occupant health and comfort;
- Reducing strain on local infrastructure; and
- Contributing to overall quality of life (US GB Council 2009)

2. **Economic Benefits:**

- Minimizing operating costs;
- Enhancing profits and asset value;
- Improving employee productivity and satisfaction; and
- Optimizing life-cycle economic performance (U.S. G.B. Council 2009)

3. **Environmental Benefits:**

- Enhancing and protecting biodiversity and ecosystems;
- Improving water and air quality; Minimizing solid waste; and
- Conserving natural resources (U.S. G.B. Council 2009).

Many studies have documented green building benefits, such as: "Health and Productivity Gains from Better Indoor Environments", where Fisk (2000) summarized that greener indoor environments will reduce losses in productivity and costs of health care by 9 to 20% for communicable diseases, 18 to 25% for decreased asthma and allergies, and 20 to 50% for other discomfort and health issues.

The Heschong Mahone Group (1999) discovered that students with the most natural day lighting in their classrooms did 26% better on reading tests and 20% better on math tests compared to students with extensive artificial lights in their classrooms.

Milton conducted a study on the risk of sick leave associated with outdoor air supply rate. It shows that sustainable green buildings will decrease absenteeism rates by 35% (Milton, 2000).

HMG (2003) discovered that maximizing natural daylight will improve and increase worker productivity by 13%. Glare from windows reduces performance by 15 to 21%, and efficient ventilation increases performance by 4 to 17%. Furthermore, their study shows that providing a pleasant and sufficient view is associated with better office work performance. On tests of mental function and memory recall, office workers performed 10 to 25% better when they had an enjoyable view.

Kates (2003) established a correlation between improved productivity and lighting control, improved productivity and ventilation control, and improved productivity and temperature control.

Another study established that student learning improved with pleasant views, and that glare and direct sun penetration influence student learning negatively (HMG, 2003). This study also summarized that the acoustic environment is significant for learning, and that poor ventilation and indoor air quality decreased student performance.

Furthermore, Hathaway et al. (1992) proved that daylight influences students' performance positively, improves health, and reduces absences. Students in natural light classrooms attended 3.5 days more per year, and were quieter than students in classrooms with more artificial lights.

Kats (2005) introduced a comprehensive study in the sustainability and green benefits field. It proved that 70 to 78% of total whole-life cost savings can be estimated for the increases in productivity and decreases in health costs in green buildings, based on the sustainability level of the buildings considered.

2.3.2.2 Challenges in Implementing Sustainability

Despite the obvious social and environmental benefits of implementing sustainability principles, and despite the increasing research in this field, professional's in the fields of architecture engineering, and in the construction industry are still unwilling to invest all of their money in these developments (Issa, 2009). This is due to an extra cost premium for green buildings that discourage practitioners from implementing them, and because of the unclearness of sustainability practices' effect on the whole life-cycle costs (WLCC) of facilities. Practitioners still neglect the long-term economic benefits of green buildings in favour of short-term design and construction costs and savings. Moreover, they continue to ignore the benefits of green buildings in the long-term operating, maintenance, rehabilitation, and usage costs of those buildings. This still tends to happen despite the huge value of these costs and the major savings predicted by some researches in the long-term costs of green buildings (Issa 2009). To sum up, constructing sustainable buildings usually requires using new materials, extra site precautions, higher construction standards, and a typical project management methods (Siddiqi et al., 2008).

2.3.3 Sustainability Measurement Tools

The first group of sustainability and environmental impact measurement tools includes those that depend entirely on criteria scoring systems. These scoring systems are rather subjective scoring systems that have assigned point values to a number of selected parameters on a scale ranging from small to large environmental impact (Assefa et al., 2007). The main principles of sustainability developments are: reuse resources, decrease resource consumption, protect nature, use recycled resources, eliminate toxicity, apply life-cycle costing, and focus on quality (Sinou 2006, Kibert 2005). The majority of green building criteria scoring systems take into account different categories such as site selection, efficient use of energy and water resources during operation, reusing and recycling of materials and water, waste management throughout construction and operation, indoor environmental quality, passive cooling and heating, and ventilation. Several environmental tools and methodologies for evaluating the environmental impact and performance of buildings are presently being developed. On a worldwide scale there are some common criteria scoring systems such as SBTool (Sustainable Building Tool), which is an international project that emerged in and is coordinated from Canada, LEED (Leadership in

Energy and Environment Design) a tool developed in the USA with an international application, and CASBEE (Comprehensive Assessment System for Building Environmental Efficiency), a technique developed in Japan. In Europe, some of the most commonly used systems, are BREEAM (Building Research Establishment Environmental Assessment Method) in the UK, HQE (high environmental quality) developed in France throughout the previous decade, and the VERDE technique developed recently in Spain (Sinou 2006), (Fowler 2006).

There are two different methods to describe overall sustainability performance for sustainable buildings: an array of numbers or a single number. The advantage of a single number approach is that it is very easy to use, while the array approach provides more detail. The single number approach was adopted in LEED assessment methodologies, while the array approach is utilized in SBTool, which uses a relatively large quantity of information to assess a building. The LEED scoring system results in a single number that determines the building's assessment or rating, according to an accumulation of points in various impact categories, which are then totalled to obtain a final score (Mer'eb 2008). If a single number is utilized to score a building, the system has to convert the many various units measuring environmental impacts and the building's resources (water consumption, energy use, materials, waste quantities land area footprint, and recycled materials) into a series of point values that should be calculated together to result in a single overall score that can be ranged on a scale from poor to excellent. A building assessment system can also utilize an array of numbers that result from measuring the building's performance in major areas, such as global warming potential, energy consumption, and waste generation; an overall score could then be obtained after weighting the aggregation (Mer'eb, 2008).

2.3.4 Leadership in Energy and Environmental Design (LEED)

Leadership in Energy and Environmental Design (LEED) is a criteria scoring system that was developed in the United States by the U.S. Green Building Council (USGBC) in order to meet a high-performance level by developing sustainable buildings. The USGBC is a non-profit organization that accelerates and encourages worldwide implementation of sustainable green building and development practices through the creation and adoption of universally recognized and accepted tools and performance criteria. Its main mission is to improve the quality of life by improving the methods of designing, constructing, and operating buildings and facilities, enabling socially and environmentally responsible decisions, and by providing healthy environments. LEED scoring systems are offered for many different types and statuses of buildings, such as existing commercial buildings, new commercial buildings, commercial interiors, schools, healthcare, cores & shells, retail buildings, homes, and neighbourhoods (USGBC, 2007). The LEED standard provides a single score that measures the building's rating or assessment, according to cumulative points in different impact categories, which are then computed to attain the total score. To attain LEED certification, a project must first comply with LEED prerequisite items. Then there are a range of credits that projects can attain to qualify for different LEED certification levels: certified, silver, gold, and platinum, by meeting increasing minimums point levels (Kibert, 2005). For example, in newly constructed buildings, the points range for each level is varied: 40-49 points = certified, 50-59 points = silver, 60-79 points = gold and 80-110 points = platinum. LEED certification addresses specific environmental impacts related to buildings utilizing a whole-building environmental performance and assessment approach. The main categories of criteria include: sustainable site (SS), water efficiency (WE), energy and atmosphere (EA), materials and resources (MR), indoor air quality (IQ), and innovation and design process (ID). Each category contains a number of criteria and sub-criteria, some of them are assigned a certain number of credits and others are considered as prerequisites (USGBC 2005).

LEED Canada-NC 1.0 (NC standard for new construction and major renovations) is the Canadian version of the LEED scoring system. It is approved by the USGBC and was released by the CaGBC in December 2004 (C.A. of Canada, 2007). An addendum to LEED Canada-NC 1.0 developed 2007 reflects clarifications and improved requirements introduced by the USGBC for LEED-NC 2.2, along with a few other improvements including clarifications regarding the durable building credit. The CaGBC is the source for LEED Canada updates and reference information, including templates (C.A. of Canada 2007).

2.3.4.1 LEED Implementations in Buildings

The impact of LEED-NC projects on contractors and construction management practices is the subject of research by Mago., in which a comprehensive analysis of how LEED-NC credits affect builders' activities in implementing these projects. Contractors will be able to access these impacts by using a tool of the developed database-query system. Outputs of this research were developed with the assistance of an eighteen-member industry advisory group and four case study projects. The research outputs can facilitate the builders, effectively contributing to a LEED by better understanding their responsibilities, and help contractors as they navigate LEED-NC projects (Mago 2007).

Wedding (2008) conducted research that aimed to improve the link between the LEED green building label and a building's energy-related environmental metrics. The research (1) summarizes the benefits and growth of LEED certified buildings, (2) highlights evidence of the inconsistency between the expected and actual benefits of LEED certification, and (3) suggests revisions to LEED's Energy & Atmosphere (EA) section to reduce the variation and magnitude in the energy-related environmental impacts from LEED buildings. The results of this study show that variability in impacts from LEED buildings could be reduced by 62% and the median magnitude could be reduced by 30%. In addition, impacts from LEED buildings under the proposed scheme show a 26% reduction in overlap between different LEED certification levels and a 68% reduction in impact overlap between non-LEED and LEED Certified buildings.

Attalla and Yousefi (2009) studied the construction process for a sustainable educational building. The study focused on the vital role of construction professionals in implementing a sustainable design. They also provided and documented the lessons learned from the challenges encountered by the construction team in implementing the first LEED gold-certified school in Canada. This study helps designers and construction professionals in better understanding the difficulties faced by construction managers in building facilities that are environmentally sustainable. The research also fosters the professionals' positive attitudes towards constructing sustainable educational buildings.

Hanby (2004) conducted a study to assess LEED barriers in the design and certification processes. Barriers are analyzed relative to credits, specifically credits that affect a building's form. These barriers include a lack of applicability of criteria, lack of acceptance, lack of knowledge, lack of financial backing and lack of resources. This research proved that acceptance of LEED criteria is a significant barrier to overcome in order to achieve LEED certification or credits. Cost was proven to be a significant issue that was not fully addressed, but 100% of interviewees discussed means of overcoming cost barriers to certification.

2.3.5 Life-Cycle Assessment (LCA)

The building sector has witnessed the development of two types of environmental assessment tools during the last decade. The first uses criteria scoring systems such as LEED, while the second group of environmental impact measurement tools is based on life-cycle assessment (LCA) methodology (Assefa et al., 2007). "'Life Cycle Assessment' ('LCA', also known as 'life cycle analysis', 'ecobalance', and 'cradle-to-grave analysis') is the investigation and evaluation of the environmental impacts of a given product or service caused or necessitated by its existence" (ISO 2006). The environmental performance of buildings is the main concern of professionals in the building industry and its assessment has emerged as one of the most significant issues in sustainable construction (Crawley and Aho, 1999; Ding, 2008). The development of LCA in the building sector has witnessed rapid growth; applied in two ways: assessment of building products or assessment of the whole building during the overall total life span. LCA is considered as one of the tools to help achieve sustainable building practices. When building design process is incorporated with LCA, the designer will be able to assess the life cycle impacts of building systems, materials, and components, and to select the optimum system that decrease the building's life cycle environmental impact (Glazebrook et al, 2005). Considerable work has been done to develop systems that assess a building's environmental performance during its life. These systems are developed to evaluate the efficiency of such developments, with a view to balancing the economic, environmental, social, and technical aspects (Croome 2004). There are many tools that measure and assess whole buildings based on an LCA tool, including: ATHENA (North America), ENVIST (UK), and Sima Pro (Netherland).

According to the International Organization for Standardization (ISO), LCA is divided into four major steps: goal and scope definition, inventory analysis, impact analysis, and interpretation (ISO 2006). The building itself is considered as the product under study in the case of building assessment. The whole building over one stage or over its entire life cycle is the functional unit for building LCA. The total life cycle of the building should be accounted from the extraction of the materials for construction to the final demolition of the building (Mer'eb 2008). The building life cycle consists of four main phases: site preparation, construction, operation, and demolition (Harris 1999). The total of the stages should represent the total life cycle. The building itself is broken down to the product level, and LCA is carried out from cradle-to-grave for each product. The product LCA results are added together, resulting in the LCA of the whole building. "Impact assessment is the step in which quantitative results of the inventory analysis are evaluated and aggregated into environmental loads" (Zhang, 2006).

The effects of buildings on the environment can be viewed in many forms, as shown in figure 2.6. Some of these impacts, such as dust and noise during the construction process, are transitory. Other effects are more permanent, including atmospheric carbon dioxide combustion (Harris, 1999).

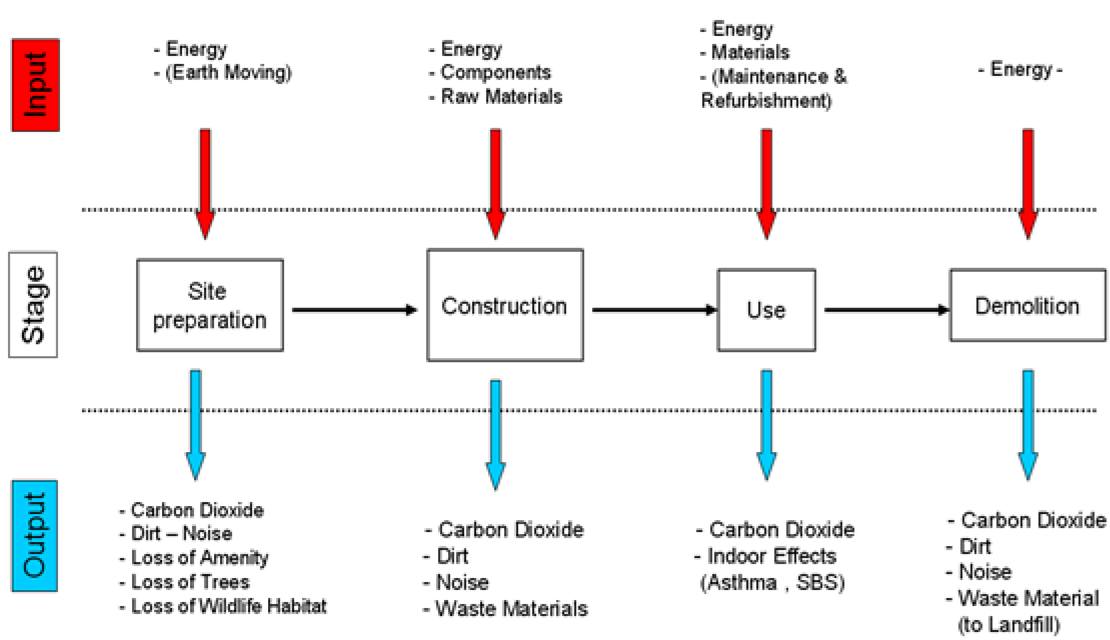


Figure 2.6 Impact of a building throughout its lifetime (Harris 1999)

The LCA technique provides a comprehensive coverage of environmental impacts and it is more beneficial in the conceptual design phase compared to the criteria scoring system. LCA tools for buildings still have some limitations and several problems, and the evaluation of the life cycle environmental impact of a building is quite complicated due to many changes and circumstances that could occur (Mer'eb 2008). Hence, predicting life cycle as "from-cradle-to-grave" for such buildings is very difficult to perform accurately for a long lifetime, such as 50 years. Furthermore, most of the buildings used in the LCA examples remain in the inventory analysis stage, e.g. identifying inputs such as energy consumption or outputs released back to the environment such as greenhouse gas emissions, (Li , 2006).

More wide-ranging building assessment techniques are necessary to measure building performance across a broader range of environmental considerations and to afford a comprehensive assessment of the environmental characteristics of a building utilizing a universal set of criteria (Best and valence2003).

2.3.5.1 Life Cycle Assessment Implementations

An environmental life-cycle assessment LCA was conducted on a single-family house modeled with two types of exterior walls: wood-framed and insulating concrete form (ICF). The LCA includes the inputs and outputs of energy and materials, from the extraction and manufacturing of materials, construction, and occupancy including heating and cooling energy use, as well as maintenance over a 100-year life. The houses were modeled in five cities representing a range of U.S. climates: Miami, Phoenix, Seattle, Washington, and Chicago. The results show that in almost all cases, for a given climate, the environmental impact in each category is worse for the wood house than for the ICF house. The reduction in environmental impacts provided by the ICF house compared to the wood-frame house varied from 3 % to 6 %, depending on the climate (Marceau 2006).

VNFT (1996) introduced a study on the environmental impact of building materials. A recent comparison of the energy used over the entire life cycle of residential buildings in four countries concluded that wood-framed buildings consume less energy than steel and concrete buildings. Timber has the lowest carbon released during manufacture, and a net positive effect when carbon stored during the tree's growth phase is included.

Townsend and Wagner (2002) presented a study into the use of sustainable timber products and how they compare to the use of materials such as steel, aluminum, and concrete, for building purposes. The paper focuses on the Life Cycle Assessment approach to building materials, exploring indicators and actual comparisons between wood and other materials. The results of a study, conducted in Germany for the Food and Agricultural Organization, clearly demonstrated that wood is the superior building material based on environmental criteria.

LCA was used to quantify the energy use and the environmental emissions during the construction phase of two typical office buildings, one with a structural steel frame and one with a cast-in-place concrete frame, and then these were put in the perspective of the overall service life of each building. Construction of the concrete structural-frame has more associated energy use, CO_2, CO, NO_2, particulate matter, SO_2, and hydrocarbon emissions due to more formwork being used, higher transportation impacts is related to a larger mass of materials, and longer equipment use due to the longer installation process. In contrast, construction of the steel-frame has more volatile organic compound (VOC) and heavy metal (Cr, Ni, Mn) emissions due to the painting, torch cutting, and welding of the steel members (Guggemos & Horvath 2005).

A study conducted by Glover (2002) proved that wood and concrete have lower embodied energy values than steel, but quite different ranges (0.6–41.2 MJ/kg for wood, 0.9–13.1 MJ/kg for concrete). Steel has a significantly higher energy value and range of values (8.9–59 MJ/kg). The wood components also had the lowest embodied energy values when these isolated component values were applied to the wall, floor, and roof assemblies. A comparison of predominantly wood, concrete, and steel houses indicates that a wood house contains 232 GJ of embodied energy; a concrete house contains 396 GJ, and a steel house, 553 GJ. An overall uncertainty calculation for each house has given the following ranges: 185–280 GJ for wood, 265–520 GJ for concrete, and 455–650 GJ for steel. Overall, mostly-wood houses appear to have the lowest embodied energy levels of the materials.

Buckely et al. (2004) used Athena™ (2003), a life-cycle assessment tool developed in Canada to compare the environmental impact of a cast-in-situ concrete system with a structural steel system for the Queen's University Integrated Learning Centre in Kingston, Canada. The case study displayed that the concrete system had less impact on global warming, toxicity, solid emissions, and energy consumption, but required greater resource use than the structural steel system. Overall, the concrete system had less environmental impact than the structural steel system.

Lippke et al. (2004) evaluated the environmental performance indicators for typical Atlanta and Minneapolis houses built to code, displaying that with two exceptions, all of the indicators had significantly lower environmental impact for the wood-frame designs in Atlanta and Minneapolis compared to the non-wood frame designs. The steel and wood designs produced similar solid waste in Minneapolis, and the concrete and wood framing designs in Atlanta produced similar water pollution. Concrete framing in Atlanta proved to have lower environmental impacts in comparison to steel and wood-framing in Minneapolis.

Finally, Haddad reported that steel framing office building has lower environmental impact than a concrete frame building (Haddad, 2008).

2.3.6 Incorporating LCA into LEED

There is a method proposed by the LCA Working Group that incorporates criteria scoring systems into LCA tools. This integration could provide major benefits such as improving accrediting and the understanding of environmental performance, and decreasing the cost and complexity of assessment (Trusty & Horst, 2002). There is also an initial recommendations development process proposed by the USGBC seeking to incorporate LCA into the LEED rating systems. The recommendations incorporate long and short-term implementation strategies and technical details for LCA methodology into the LEED system. The LCA working group's recommendation for an initial approach is to undertake the LCA of the assemblies that constitute a building's structure and envelope. The assemblies will be ranked according to their environmental impact, with LEED credits awarded accordingly. It has also been recommended to use a regional energy grid approach and not national average and energy-related emissions. The long-term objective for the incorporation of LCA into LEED: to regularly and credibly implement LCA to provide integrated design. Furthermore, the goal is to ensure environmental performance at the entire building stage, considering the total building life cycle and subject to pre-defined criteria (GreenBuildings 2007). The recommendations suggest granting credit for selecting highly-ranked products according to LCA, and that the design team should make decisions based on the LCA technique. The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) is an approach recommended to be utilized as the life-cycle impact assessment stage of LCA. The TRACI approach includes 10 categories of environmental impact: ozone depletion potential (ODP), global warming potential (GWP), photochemical oxidation potential (PCOP), acidification potential, eutrophication, health toxicity potential (noncancerous), health toxicity potential (cancerous), fossil fuel use, and eco toxicity potential (USGBC 2006a,b).

2.3.6.1 Incorporating LCA into LEED Implementations

Mere'b developed a tool to measure and subsequently improves the sustainability performance of a building over its entire life-cycle while still at the conceptual design stage. The GREENOMETER-7 is an LCA forecasting tool that evaluates a projected building at two levels: micro- and macro-assessment. The micro-assessment level provides in-depth analysis of the building products, components, and operations; while the macro-assessment level measures the sustainability performance of the building as a whole and covers areas that are not applicable at the product or component level. GREENOMETER-7 can be applied to justify LEED scores, for assessing the LEED certification level of a building at the conceptual design stage, and ensures incorporating LCA into the LEED system (Mere'b 2008).

Wedding (2007) conducted a study based on the analysis of variation in the energy-related environmental impacts of LEED-certified buildings. This research analyzes (1) how well the LEED guidelines assess environmental impacts and (2) which parameters create the most variation among these impacts. Environmental impacts refer to carbon dioxide emissions, nitrogen solid waste and water consumption. Using data from different resources, Monte Carlo analysis are applied to simulate the range of impacts of LEED-certified buildings. For an individual building category, the variation appears to be greater than what most people would consider desirable for a green building certification system. The results enabled to assess whether a series of given buildings certified at various LEED rating levels converted into a logical series of corresponding energy-related environmental impacts. For example, LEED Platinum buildings should have lower impacts than LEED Gold buildings, through this was frequently shown not to be the case.

Trusty and Horst (2002) from The ATHENA Sustainable Materials Institute introduced “Integrating LCA Tools in Green Building Rating Systems”. This paper focuses on how to accomplish the integration between LCA and some of the sustainability scoring systems such as LEED and GBTool. It includes a more detailed diagnose of the problems, with reference to the various approaches of GBTool and LEED that tends to identify the ends of the spectrum of possible approaches, a discussion of the role for LCA and ways to achieve the integration, and a brief discussion of key constraints that should be addressed and overcome. In the long run, the integration of LCA tools into whole-building assessment systems will yield significant benefits, not only in improved understanding and accrediting of environmental performance, but also in reduced assessment complexity and cost.

2.3.7 LCC Implementation in Sustainable Buildings

Even schools boards become motivated to consider applying LEED and green building principles; however, cost is still the most important concern. In an ideal world, a methodical assessment of building costs should go further than initial building construction costs which are estimated to be worth only about 5 to 10% of the whole life-cycle costs (Federal Facility Council 2001). In spite of the significance of LCC, major project decisions in the building industry are more often driven by initial construction costs alone (Matthiessen & Morris 2004).

Within the context of non-green versus a green building project, the main concern is not the total project cost, but the incremental or additional costs associated with the required green building components, over the cost of the same building without these components. This is commonly called the green cost premium which includes soft and hard costs. The soft costs include LEED registration, certification and documentation, and the related green consulting and design, while the hard construction costs include the green building components (Lisowski 2006). It becomes a big challenge to find a useful comparison that accurately determines the green cost premium for many building projects, because the green components often take the form of upgraded building systems and materials, and the LEED scoring system does not require specific project cost data (Kate 2003).

Mohan and Loeffert introduced his study “Economics of Green Buildings”. This study is conducted to review previous studies on green buildings. He has concluded that previous studies have displayed that green buildings could save about 30% in minimizing utility bills over conventional buildings. In addition to direct savings in energy costs, green buildings have the potential of lower insurance premiums, lower waste disposal charges, reduced water and sewer fees, and increased rental rates. Green buildings are designed to be environmentally healthy and energy efficient. However, their initial cost can be 1 to 5% higher than the conventional buildings (Mohan & Loeffert 2011).

Sullivan's study investigates initial costs and design outcomes in pursuing LEED certification for new commercial construction in the state of Florida. The study notes the two greatest drivers determining first costs are the project-specific LEED credits selected, and the degree to which current building standards and practices meet those required by the USGBC. The model incorporates a Logical Scoring of Preferences (LSP) method that evaluates decision makers' preferences and cost separately and then combines preference rankings and costs to provide a range of costs and sustainable impacts. Each LEED credit is automatically conceptually estimated based on a limited number of project-specific inputs. The resulting output presents certification benchmarks and cost ranges for the evaluation of LEED alternatives (Sullivan 2007).

Lisowski studied the application process to the LEED green building rating system for small to medium-sized enterprises, SME. This study presents a LEED business case and project analysis structure that an SME can adapt to its own business conditions, and then arrive at its own credible conclusion regarding the long-term value of a green building. This study was conducted for different LEED-rated office buildings. The case study was the region of Waterloo Emergency Medical Services, which earned LEED - Gold certification. The green cost premium was estimated to be CAD $384,000 in 2004, which represents 12.8% of the total project cost, which may appear to be relatively expensive. The purpose of the case study was to examine the financial aspects for the project and estimate post-construction cost data by making a LEED point-by-point cost analysis for the project. The result of this case study shows that reducing the green cost premium from 12.8% to 7.7% it is still possible to achieve LEED-Gold level. Green cost premiums of 3% to get a LEED-Certified level and 4.6% to get a LEED-Silver level are also possible. The project models are presented within two groupings: group one, which are differentiated by both the number and type of LEED points achieved; group two, which are differentiated by building size. The cost-benefit comparisons are presented, including NPV, IRR, and payback period. The project cost premiums are as shown: CS-Certified 3.3% ($100,000), CS-Silver 4.6% ($138,000), BC-Certified 4.0%, ($120,000), BC-Silver 5.8% ($176,600). The best investment is BC-Certified with cost premium 4% ($120,000), NPV of $40,000, IRR 12.8%, and payback period of 8 years. For the second group, projects have different sizes: 5000 sqf, 8000 sqf, 12,000 sqf, and 22,000 sqf. The best investment is the largest area with NPV = $50 000, IRR 9.1%, and payback period of 10 years. The smaller project models resulted in mostly negative NPV, longer payback periods, and lower IRR (Lisowski 2006).

McDonald (2005) investigated the economics of green buildings in Canada via estimating the initial cost premium of five case studies located various provinces across Canada, including building LEED certified building. McDonald proposed seven keys to cost-effective green building: get into a sustainable mindset, establish a clear vision and define the goals, integrate the design process, diffuse knowledge, apply LCC & tunnel through the cost barrier, compensate with brains not stuff, and follow the money trail. The result of this proposal shows that green building is less about product and more about process. Results from five case studies shows that the capital cost of green buildings is 5% less than conventional buildings.

Indian Health Services (IHS) conducted a study to evaluate the potential cost impacts of achieving basic and/or silver LEED certification for their facilities. Both initial costs and life-cycle costs (LCC) were evaluated. This study examined the cost impact of each applicable LEED credit, based on existing IHS program standards. The study also demonstrated the LCC for each credit. Additionally, it compared its findings with that of the GSA report. This gives insight as to how the LEED process impacts two different building types developed under two different building programs. The result of this study shows an anticipated cost impact between 1.0 and 7.6 %, depending on the level of certification desired. A 3.0% increase to the construction budget would be appropriate to pursue a basic LEED certification. Over a 20-year life cycle, there is a potential for savings in the O&M budget – principally in the form of energy savings (IHS, 2006).

Matthiessen and Morris (2004) conducted a study on the comparison of green versus non-green buildings. Forty-five library, laboratory, and academic classroom projects, designed with some level of LEED certification, were selected for comparison with 93 non-LEED projects of similar types. All costs were adjusted for location and time of construction. Given the common perception that cost of LEED projects is more than non-LEED projects, the analysis was striking. The results displayed no statistically significant difference between LEED and non-LEED projects (Sullivan 2007). The LEED projects were dispersed through the range of all projects based on cost. It is important to note that the standard deviation of building square footage costs was high, based on the different types of buildings and different square footages of the sample buildings. Ten random non-LEED projects were selected from the original list of 93. The ten buildings scored between 15 and 29 points based on the LEED scoring system. The project that scored an estimated 29 points would have surpassed the necessary 26 points needed to achieve LEED certification. Overall, the study indicated that typically, 12 LEED points can be earned without changing design, based on the location or siting of a building and local code requirements. Furthermore, up to 18 additional LEED points may be accomplished with minimum design effort at little or no additional cost (Matthiessen 2004).

A common way to determine the green cost is to compare the project's final budget with the initial budget. This tends to include all cost overages, not only those associated with 28 LEED points. Over half of the projects studied had no additional costs allocated for LEED and came in within budget. The remaining projects had additional monies set aside for items such as photovoltaic systems and other special enhancements. These projects' additional 'green' supplements ranged between 0.0 and 3.0 percent of their initial budget.

Kats (2003) studied the "Costs and Financial Benefits of Green Building", Cost data was gathered from 33 individual LEED-registered projects (25 office buildings and 8 school buildings) with actual or projected dates of completion between 1995 and 2004. Kats demonstrated conclusively that sustainable building is a cost-effective investment, and his findings should encourage communities across the country to “build green.” This report assumes a 20 year term for benefits in new buildings’ inflation. This analysis assumes an inflation rate of 2% per year and a 7% discount rate (i.e., 5% real interest rate plus an assumed 2% inflation). Relatively high California commercial construction costs ranged between $150/ft² to 250/ft². A 2% green building premium is the estimated average, which is equivalent to $3-5/ft². The green buildings tested here provided an average 30% reduction in energy use, as compared with the consumption associated with minimum energy code requirements. For energy costs of $1.47/ft²/yr, this indicates savings of about $0.44/ft²/yr, 117 with a 20-year present value of $5.48/ft². The additional value of peak demand reduction from green buildings is estimated at $0.025/ft²/yr, with 20-year present value of $0.31/ft². This report assumed the lower $5 per ton value of carbon, indicating a 20-year PV of $1.18/ft² for emissions reductions from green buildings. Green buildings also provide a 20-year PV of $0.51/ft² for water savings. Calculating rough conservative values for C&D diversion in new construction was $0.03/ft² or $3,000 per 100,000 ft² building for construction only. To be conservative, this report assumes that green buildings experience an O&M cost decline of 5% per year. This equals a savings of $0.68/ft² per year, for a 20-year PV savings of $8.47/ft². Productivity and health values for LEED-certified and silver-rated buildings shows savings of $36.89/ft², while in LEED-gold and platinum show these values show a savings of $55.33/ft². The data indicates that the average construction cost premium for green buildings is almost 2%, or about $4/ft² in

California, substantially less than is generally perceived. As a conclusion, the NPV for a 20-year time period shows total estimated savings of $48.87/ft² for LEED-certified and silver, and a total estimated saving of $67.31/ft² in LEED-gold and platinum levels.

Issa et al. (2011) conducted study entitled “Evaluating the Long-Term Cost Effectiveness of LEED Canadian Schools”. Study consists of 20 energy-retrofitted, 3 LEED certified, and 10 conventional Toronto schools were compared over a maximum study period of eight years. The results of analysis displayed that green schools and energy-retrofitted consumed about 37% more on electricity than conventional ones. On the other hand, green schools consumed 41% and 56% less on gas than energy-retrofitted and conventional schools respectively. Furthermore, Energy-retrofitted schools consumed about 25% less gas than conventional ones. Total energy costs were 28% lower in green schools, whereas they were similar for conventional and energy-retrofitted schools. Finally, The maintenance, operating, renovation and total costs of green schools were also 20%, 17%, 32%, and 25% lower than conventional schools respectively, and 12%, 14%, 16%, and 14% lower than energy-retrofitted schools respectively.

2.3.8 Summary and Limitations in the Literature

LCC is a technique utilized to estimate a whole building’s costs, such as: initial costs, operating, maintenance, major repairs, and salvage value or demolishing costs over the total project life span. Many studies have been conducted in the implementation of LCC in construction projects, buildings, infrastructures, and facilities management, and other studies show some benefits that can be obtained by its implementation. This technique is helpful to evaluate alternatives, and results in the selection of the most economically viable option. Many LCC models have been introduced in the literature, taking into account the functions and elements of buildings. However, factors that affect LCC such as structure and envelope type, LEED's level and scores, energy costs, and climate zone have not been considered in these models. Most of these models are based on office buildings without a focus on or only small attention to school buildings.

Sustainability focuses on minimizing building impacts on the environment and on promoting human health throughout a building's lifecycle, through better siting, design, construction, maintenance, operation and demolition (William 2005). Many of the studies that have been conducted present several benefits that could be obtained from applying sustainability and green development to major aspects such as social benefits, economic benefits, and environmental benefits. Some studies show the challenges that face the implementation of sustainability in construction, such as the additional premium costs of sustainable buildings and the uncertainties of the impact of this practice on the total life cycle costs, which indicates that these matters require extra effort and more research. Furthermore, efforts in the literature focused on the sustainable design process without a focus on or at least very little attention to the selection of sustainable structure and envelope type of school buildings.

The LEED standard is a technique utilized to measure the sustainability level of existing and newly-constructed buildings. There are very few studies on LEED certification that measure and evaluate different structure and envelope types, and the level or scores of LEED that can be achieved by applying each one. In 2008 and 2009, the number of LEED certified schools in the United States and Canada jumped from 30 to 150 schools, which calls for more research regarding the cost effectiveness of these green schools. LCA is a sustainability tool which measures the environmental impacts of buildings and building components. Most of the studies conducted on LCA for different structure types show a variety of resulted environmental impacts, which requires further studies. In addition, most of the comparison studies that have been done on LCA did not take into accounts the other sustainability categories and principles, such as recyclability and energy optimization.

Incorporating LCA into the LEED rating system remains under investigation, even though both are considered to be vital sustainability measurement tools. In this study, LCA will be assigned LEED scores in order to achieve a high level of sustainability.

LCC and sustainability have been investigated individually in the majority of the previous studies. In the proposed study, these two techniques will be integrated and investigated together in order to select the optimum structure and envelope type for school buildings from two points of view: LCC & LEED. Also, LCC forecasting models will be developed for conventional and sustainable schools to assist schools boards to predict the overall costs of the new school buildings.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter introduces the applied methodology for data collection, the analysis process and the different techniques and tools that were used to test the various alternatives towards achieving the main goals of this study.

3.2 Conducted Study

The main contribution of this research is to develop a tool that would assist school boards to select the favorable structure and envelope type for new school buildings from two points of view: LCC and sustainability. Furthermore, the conducted research enables school boards to predict the LCC of their new buildings through developing deterministic and probabilistic forecasting models. This research was applied on two types of school buildings: conventional and sustainable ones. Fourteen different structure and envelope types are investigated: concrete, steel, wood, and composite material. The process of analyzing conventional school buildings consists of developing two models, namely: life cycle costs forecasting model and sustainability assessment model. Four main criteria were investigated in LCC model, including: initial costs (construction costs), running costs (energy ,operating and maintenance, and major repairs costs), environmental impact costs, and salvage value as shown in Figure 3.1. The sustainability assessment model consists of three major categories of LEED standard’s, such as energy and atmosphere (energy consumption), material and resources (recyclability and reuse of material), and innovation & design process (life cycle assessment).

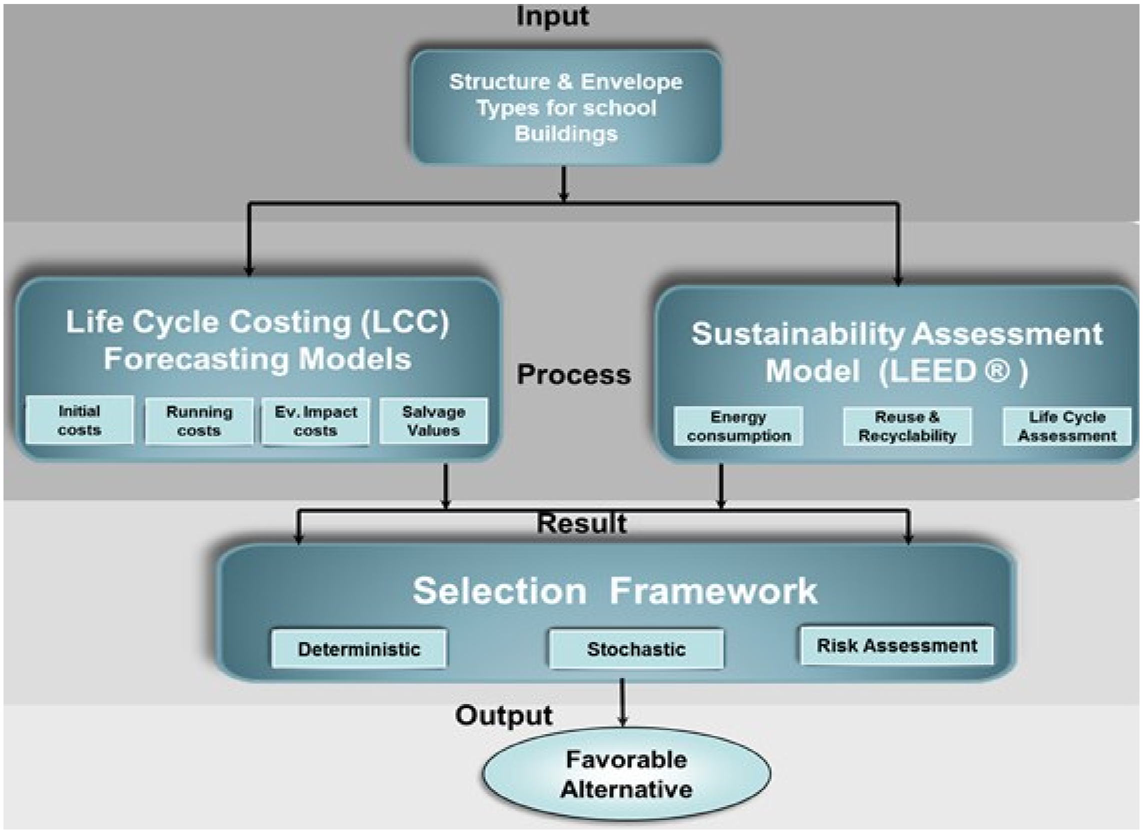


Figure 3.1 Proposed Methodology for conventional school buildings

The evaluation of sustainable school buildings passes through the same evaluation process of conventional buildings, with the addition of the sustainability criterion that assesses the total obtained sustainability scores of existing LEED certified buildings addressing all sustainability categories. Consequently, the developed life cycle forecasting model and sustainability assessment model resulted in developing of selection framework. This framework is developed based on experts' judgments using two estimating approaches, deterministic and stochastic with regards of the acceptable or the required confidence level. Risk assessment is then applied to enhance the selection of the most attractive alternative based on the net present values or the most significant criteria.

The selection framework will assist in the selection of the favorable structure and envelope type for each criterion by measuring the performance of each alternative and comparing it to other alternatives. For example, decision makers who are concerned mainly about the initial costs, they will be able to select the best alternative that achieves the minimum initial costs. In addition, the developed selection framework will assist in the selection of the favorable structure and envelope type that achieves all of the criteria integrated together, as shown in Figure 3.2.

The sustainability assessment model, SAM, is developed to assess the possible obtained sustainability level (LEED score) that can be achieved by the various tested conventional alternatives. The LCC forecasting models, LCCFM, will enable school boards to predict the life cycle components costs for the various alternatives and their net present values. These models are powerful tools that can be applied on new school buildings in the decision analysis stage. For instance, school boards will be able to predict the life cycle components' costs and achievable LEED score that are associated with various combinations of structure and envelope types, such that they can select the attractive alternative for them.

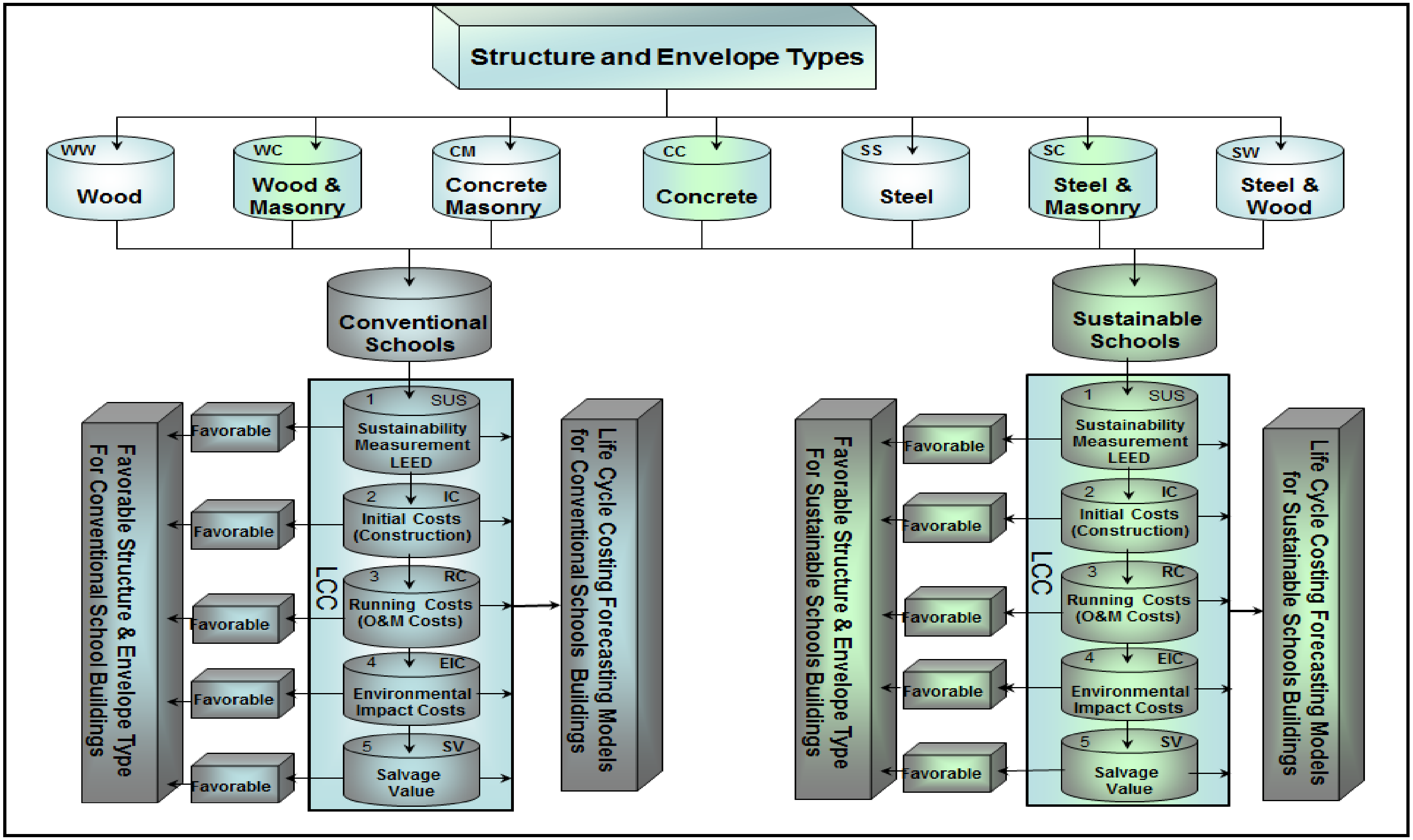


Figure 3.2 Applied Methodology Frameworks for conventional and sustainable school buildings

3.3 Investigated Structure and Envelope Types

There are many structure and envelope types that can be used to construct school buildings in the United States and Canada. The selection of each structure type is governed by many aspects such as location, material and resource availability, weather conditions, material and labour costs, and material life span. Table 3.1 shows various tested structure and envelope types that are commonly used in school buildings in North America. These alternatives consist of three main materials, namely: concrete, steel, and wood whether they are alone or in various combinations. Figures 3.3-3.9 display the detailed sections for the different investigated alternatives.

Table 3.1 Tested Structure and Envelope Types

Alternatives		Frame Type	Wall Type	Floor Type	Roof Type
1-	CC	Precast concrete	Precast concrete panels	Hollow core slab	Hollow core slab
2-	CM	Reinforcement concrete	Face brick with concrete block	Solid concrete slab	Solid concrete slab
3-	WC	Wooden frame	Face brick with GYP BD	Wooden floor	Wood roof on Wood trusses
4-	WW	Wooden frame	Wood siding with wood studs	Wooden floor	Wood roof on Wood trusses
5-	SW	Steel frame	Wood siding on Wood studs	Concrete/metal deck/metal joists	Metal deck on open web joists
6-	SS	Steel frame	Steel siding on steel studs	Concrete/metal deck/open joists	Metal deck on open web joists
7-	SC	Steel frame	Face brick with steel studs	Concrete/metal deck/open joists	Metal deck on open web joists

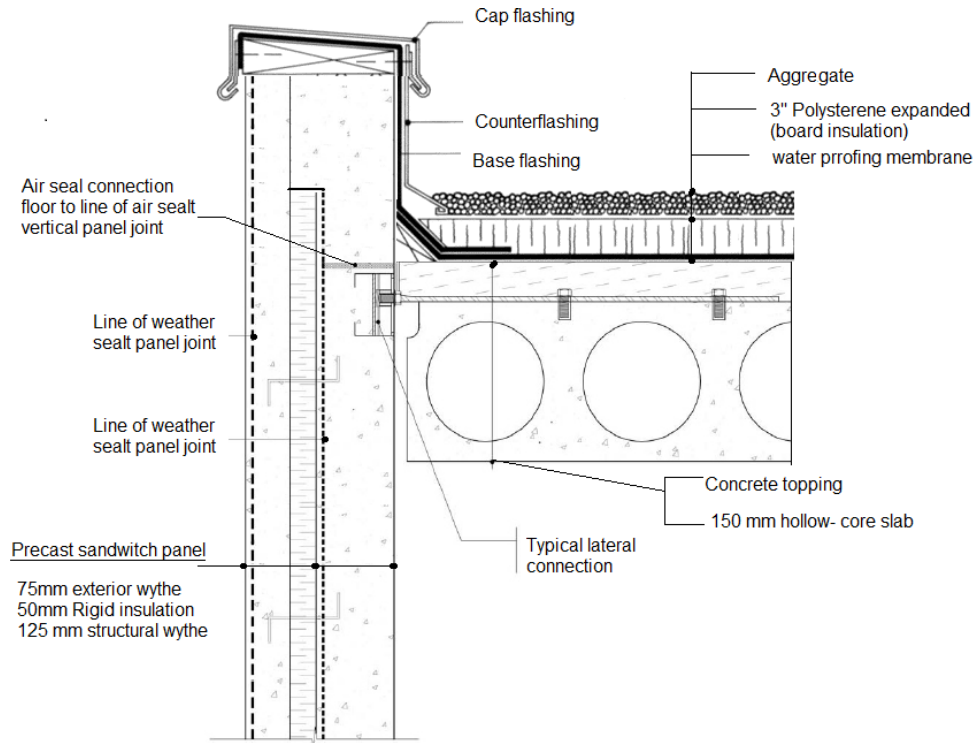


Figure 3.3 Detailed section for precast concrete alternative (CC)

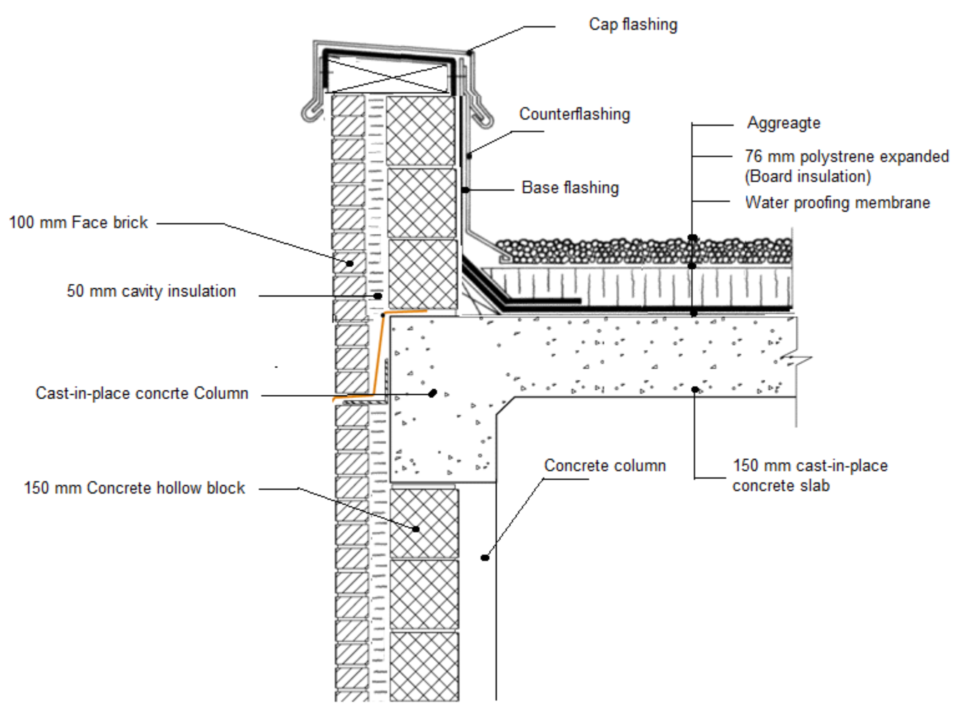


Figure 3.4 Detailed section for masonry concrete alternative (CM)

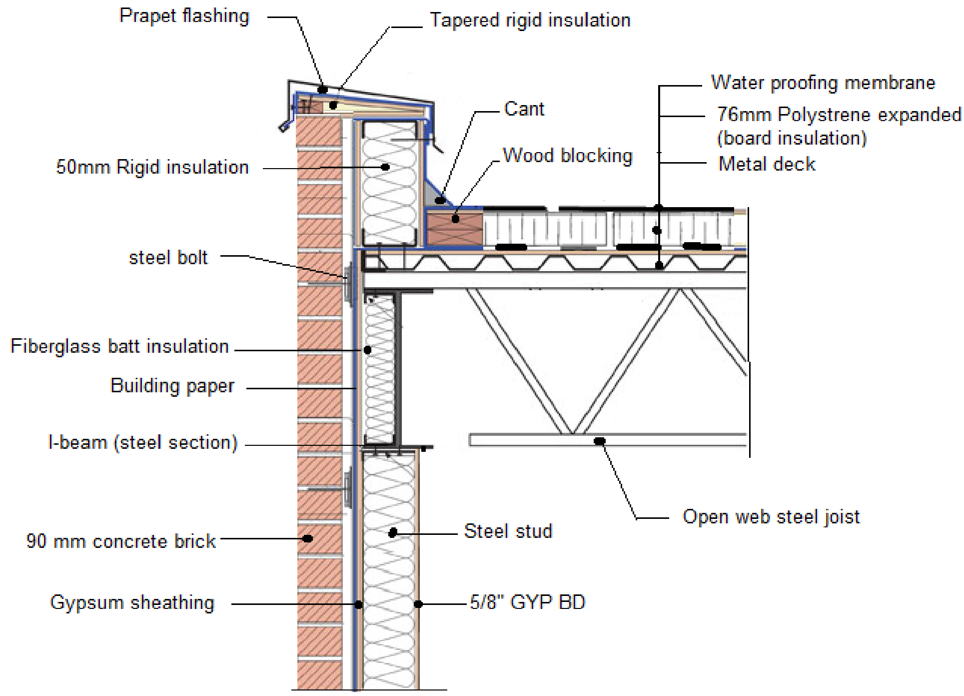


Figure 3.5 Detailed section for steel alternative with brick (SC)

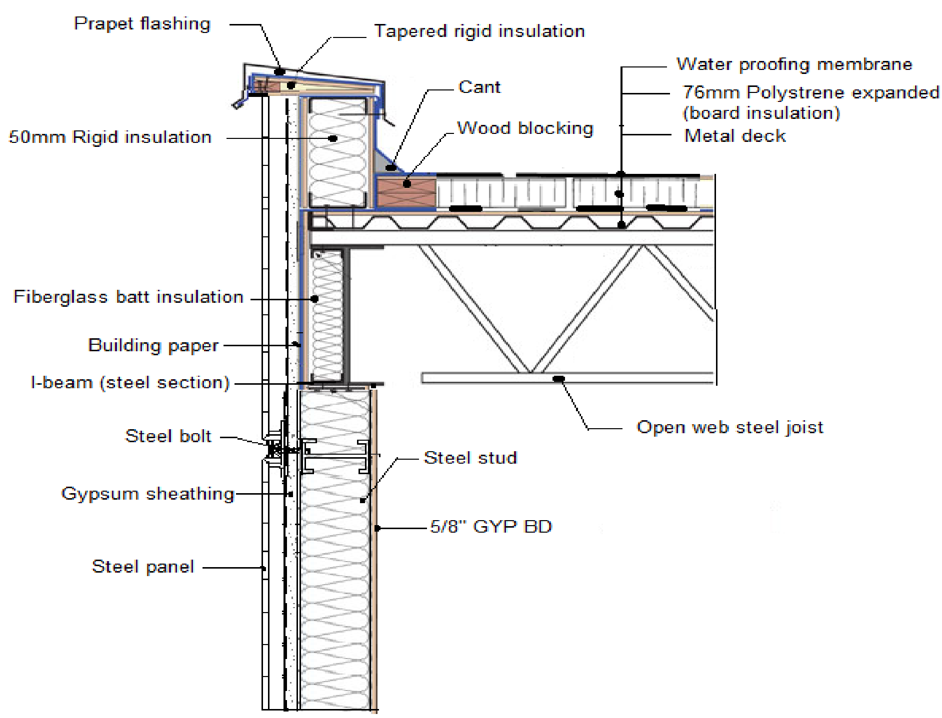


Figure 3.6 Detailed section for pure steel alternative (SS)

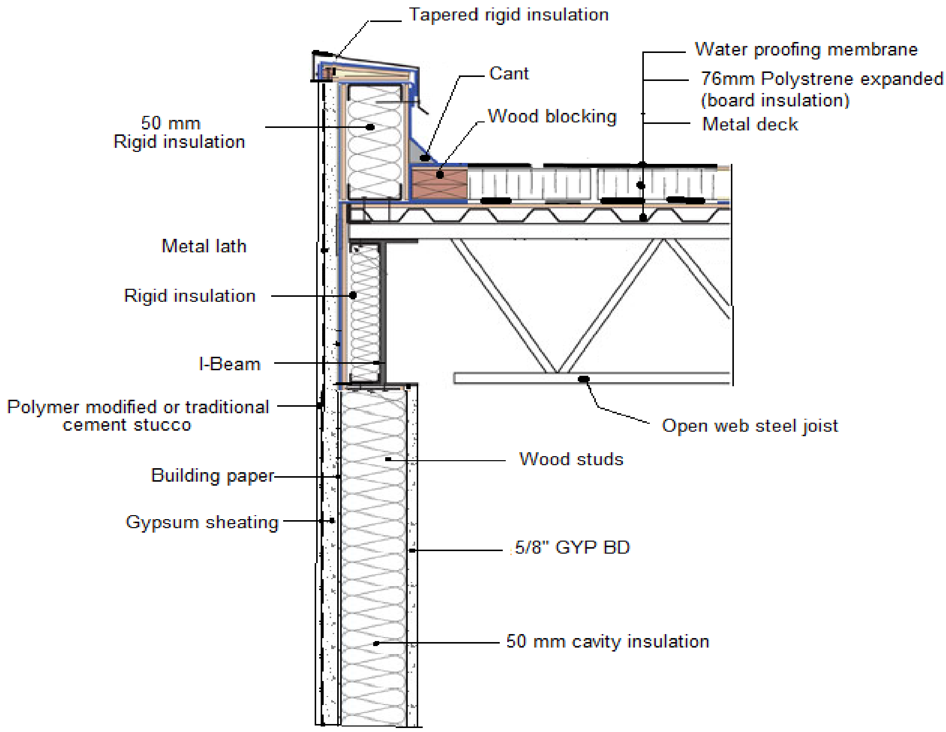


Figure 3.7 Detailed section for steel alternative with wood wall (SW)

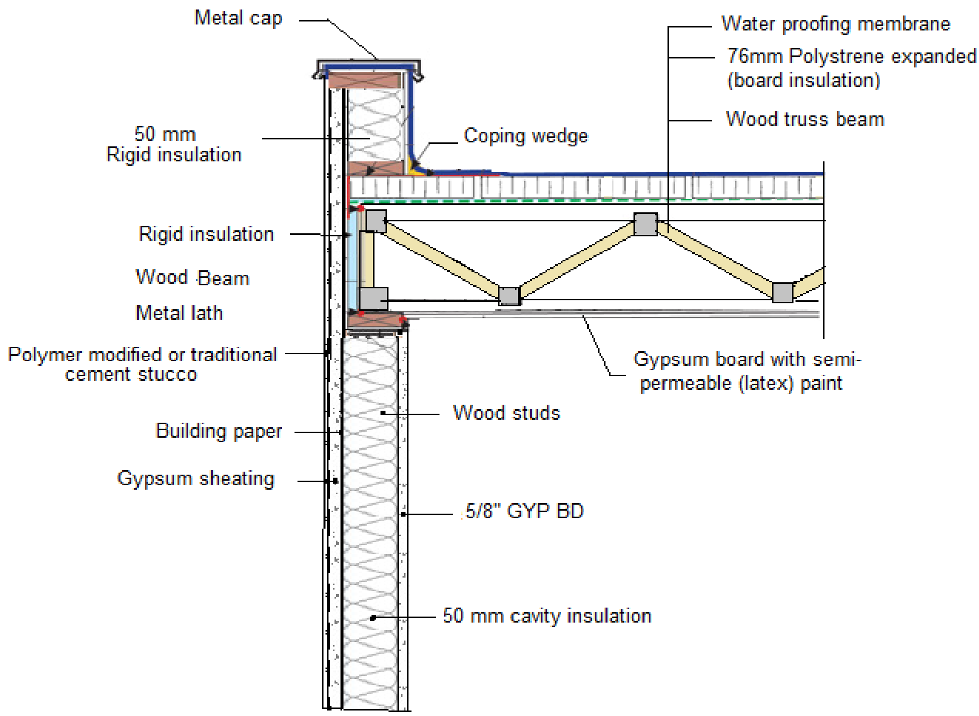


Figure 3.8 Detailed section for pure wood alternative (WW)

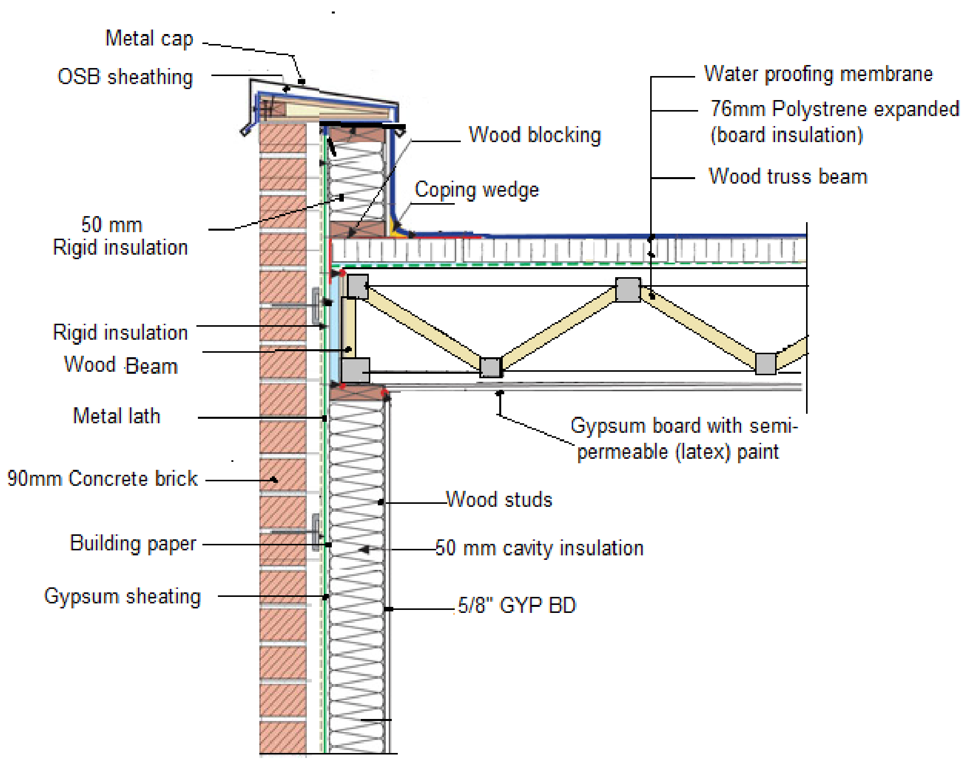


Figure 3.9 Detailed section for wood alternative with concrete brick (WC)

3.4 Life Cycle Cost Components for a Typical School

Life cycle cost components for school buildings can be broken down into several elements in a hierarchy structure, as shown in figure 3.10. The first level has the major costs: initial costs, running costs, and salvage value. Since parties in the Kyoto Protocol committed to reach their targets through reducing GHG emissions over the (2008-2012) commitment period and since the Protocol allows countries that have emission units to sell this extra capacity to countries that are over their targets (United Nations, 2011); Thus, environmental impact costs are added as future costs, and computed based on the prices and quantities of GHG converted into CO_2 e.

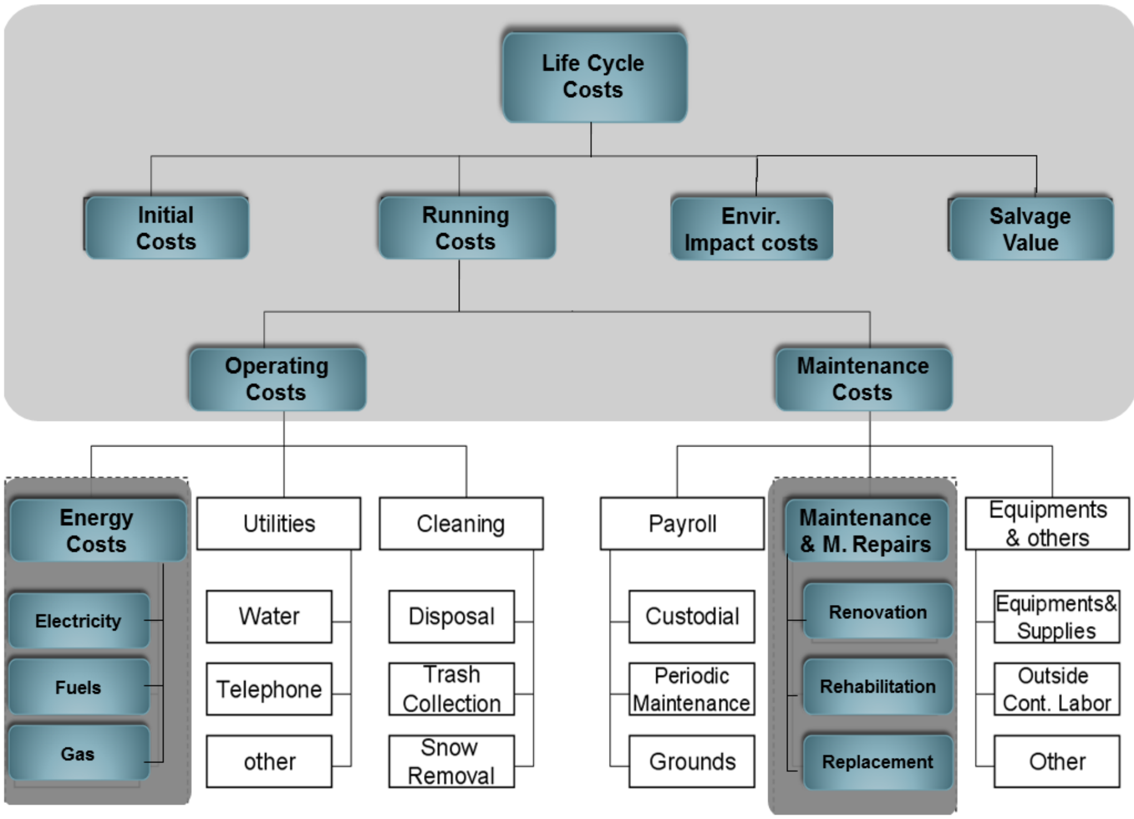


Figure 3.10 Life Cycle Costs Components for A Typical School Building

The second level consists of operating and maintenance costs, which can be broken down into elements. For example, operating costs include energy costs, utilities, and cleaning costs, while maintenance costs include major maintenance and repair costs, and other costs such as equipment and supplies.

buildings structure and envelope types have a major influence on the life cycle costs, especially the initial costs and operating costs such as energy, major maintenance and repair, environmental impact costs, as well as the salvage values. Hence, those costs are the major costs that were investigated deeply in this study. The other running costs for schools that are not governed by structure type, such as utilities, cleaning costs were collected from school boards in

Montreal. The following definition includes some of these costs that are not described clearly in the previous hierarchy cost structure for a typical school.

Custodial: The salaries and benefits for those responsible for building upkeep and cleaning;

Periodic Maintenance: The cost of contractors (or school-system employees) who perform skilled jobs, such as HVAC, electrical or plumbing repair;

Grounds: The costs of landscape upkeep and maintenance (employees or contractors);

Outside contract labor: Those hired for specialized jobs to maintain or repair specific building systems or equipment (for example, roofers, masons);

Other: Most often identified as clerical/office costs, employee training, equipment repair and rental, insurance and travel;

Equipment and Supplies: for custodial, maintenance and grounds services. (Agron, 2008)

3.5 Developed Selection Framework Methodology

Selection framework was developed in this research based on experts' opinions that were gathered through designed web-based questionnaire. Figure 3.11 displays the development of selection framework process. First step in this process of framework was to measure the performance of all alternatives over the selection criteria. The criteria were evaluated and weighted based on their significance, established by applying the AHP technique to calculate the obtained importance weight for each criterion based on the responses to surveys distributed to decision makers and experts at schools boards. The MAUT technique was applied to determine the utility preference values, and to build utility graphs for each criterion. These developed utilities graphs were applied to be used to rank and judge the performance of the alternatives. The resulted scores of each alternative were obtained by multiplying the criteria weights by the performances of those alternatives. Finally, the total highest score is selected as the favorable alternative, as shown in Figure 3.11.

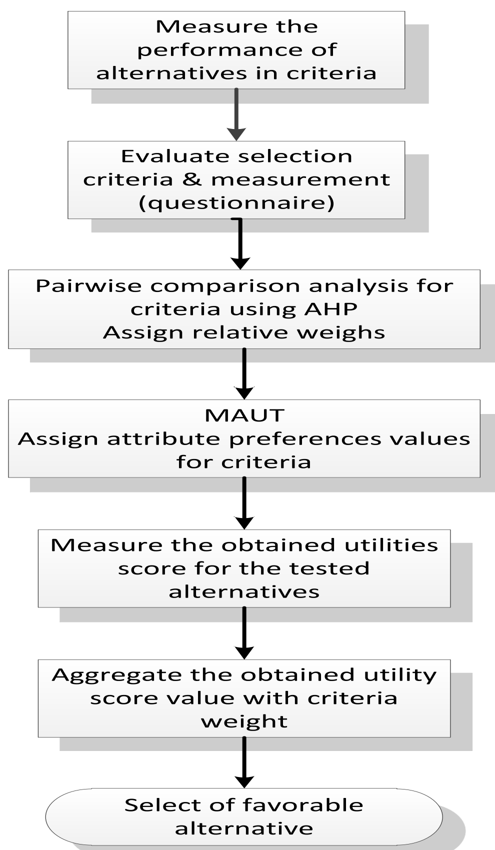


Figure 3.11 selection framework development process

3.5.1 Selection Framework for Conventional School Buildings

The selection framework was developed by evaluating the performance of seven structure and envelope types as given in Table 3.1 (steel, concrete, and wood, in various combinations) against particular criteria. The first criterion was investigated in this study sustainability, which was measured by applying the LEED rating system. Three main categories were tested in the research: energy and atmosphere, was measured via energy simulation software (eQUEST); materials and resources, was collected from the existing LEED certified schools; life-cycle assessment, was measured by ATHENA software. The process then was passed through the second criterion test, that of initial costs; these costs were calculated using RS Means. Several regression models were developed for the alternatives based on RS Means. The third test was the running costs, which include operating and maintenance costs that were gathered from schools boards along with the energy consumption, estimated by energy simulation. The next tested criterion is environmental impact costs which was calculated based on structure and envelope material, energy consumption, quantity, and market price of resulted CO_2e. The final step was to compute salvage values of alternatives; whereas the depreciation approach was obtained from real estate agencies, while the expected useful life was collected from RS Means. The developed selection framework converts the various measurement units into unified one (utility score). The final result of this framework will assist schools' boards in the selection of favorable structure and envelope type that achieves the highest score over the whole body of tested criteria, as shown in Figure 3.12.

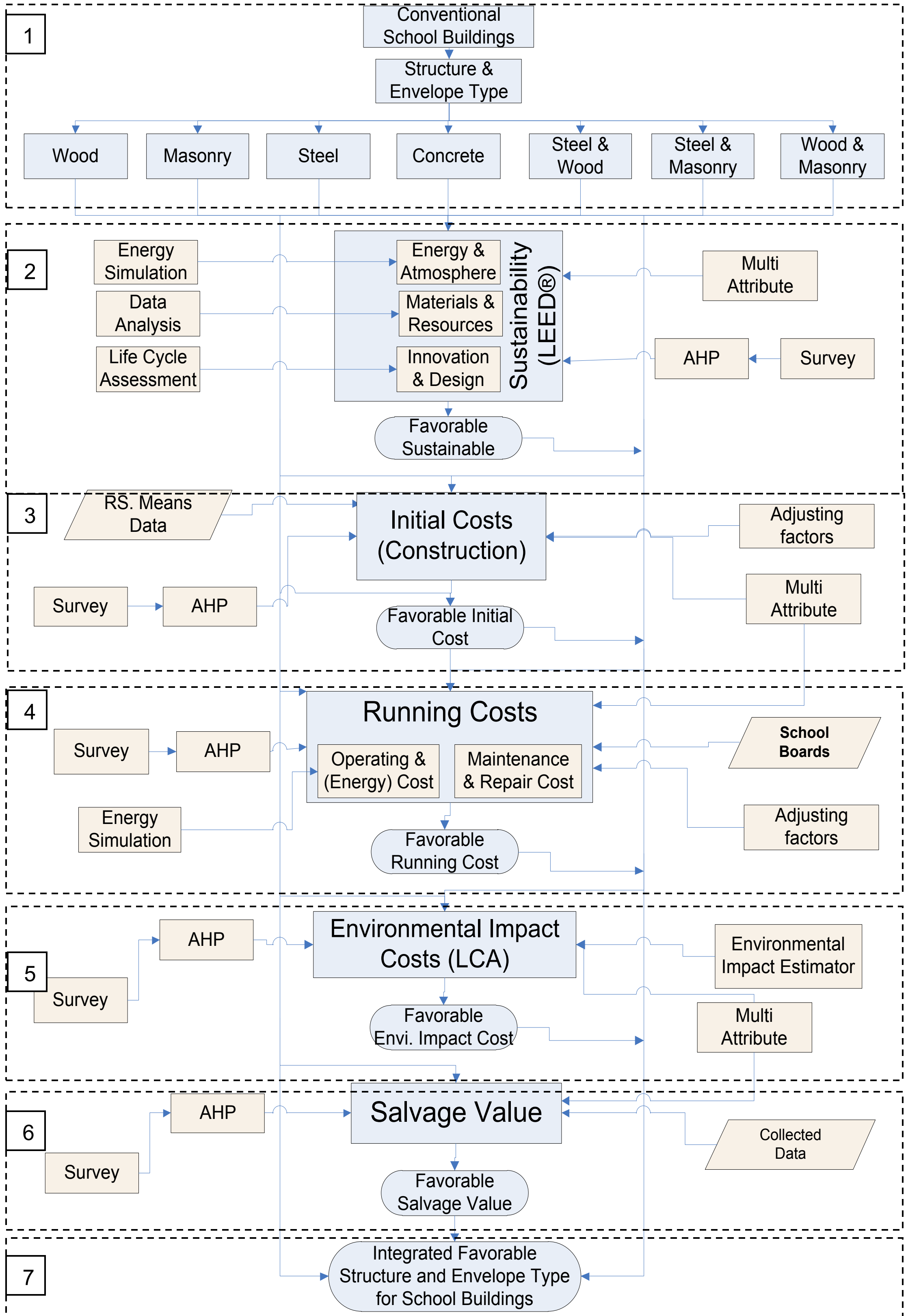


Figure 3.12 Selection Framework Flowchart for Conventional School

3.5.2 Selection Framework for Sustainable School Buildings

The process of the selection of sustainable school buildings consists of seven stages, as shown in Figure 3.13. The first stage contains the alternatives, which includes seven structure and envelope types: steel, concrete, wood structures, and combinations of these materials. The second step is where the sustainability level, represented by the sustainability scores and levels according to an evaluation by LEED scoring system, is indicated. These LEED scores and levels vary from bronze (26-32), silver (33-38), and gold (39-52), to platinum (53-69). The sustainable alternative was determined according to the highest average obtained from the LEED scores. The third stage in the process is the initial costs test, which evaluated the capital costs for the existing green and LEED®-certified schools. The data for these schools was gathered from US and Canadian green building councils and schools boards. The average and probability distribution of initial cost in ($/ft^2) for each alternative was estimated and adjusted to a particular year and city. The fourth step is evaluating the running costs, including maintenances and major repairs costs, which were adjusted and estimated for the collected data from school boards. The operating costs were gathered from green building councils and school boards. The fifth step is to compute the environmental impact costs for LEED certified schools. The sixth step in this process is to determine the salvage value of a building, and this was computed as conventional schools. The final step is selecting of the favorable structure and envelope based on AHP & MAUT. This selection was obtained using deterministic and stochastic approaches, as well risk assessment technique.

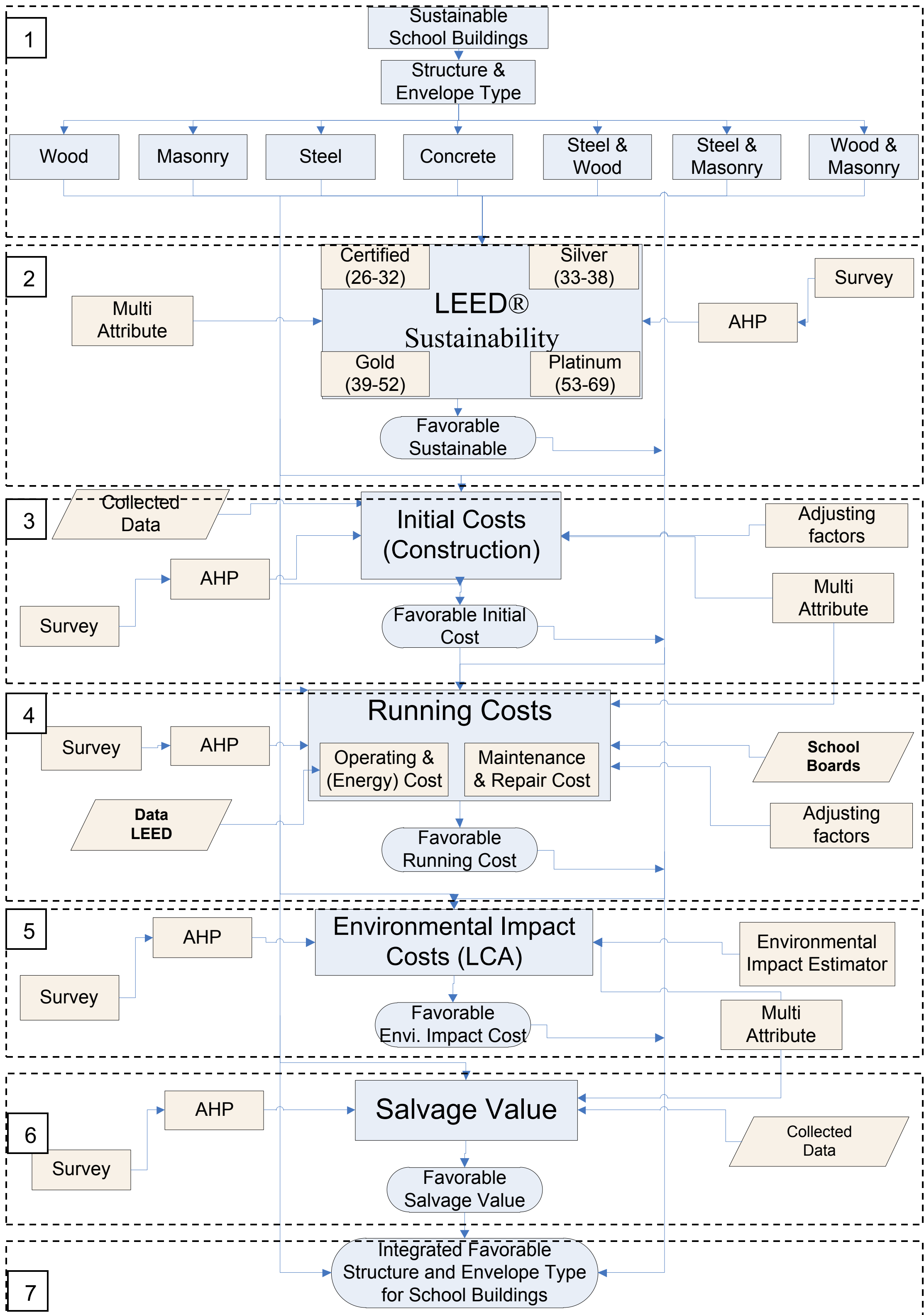


Figure 3.13 Selection Framework for Sustainable School Buildings

3.5.3 LCC Forecasting Model for School Buildings

LCC forecasting models will enable users, owners and schools boards in North America to predict the costs of their new school buildings. There are several factors or parameters that govern the LCC of school buildings. These include:

- **School level:** elementary, middle, or secondary school;
- **School Area:** includes the building area in square footage;
- **Numbers of floors**: which range between 1 to 4 floors (maximum height of wooden buildings);
- **Climate zones**: there are eight climate zones in North America, based on the ASHRAE standard;
- **Location city**: this parameter is vital because the cost index of a location varies in different cities;
- **Year built**: this parameter includes the projects that are built within the study period;
- **Structure & envelope type**: includes steel, concrete, and wood, in various combinations; and
- **Utilities rates:** these rates include electricity, gas, and CO_2 rates.

Some of the above-mentioned criteria were taken into account before developing the forecasting model, while others will be dealt with as part of the model. Some other parameters that affect LCC analysis have also be determined, such as discount rate, inflation rate, and study period. Figure 3.14 displays the developed LCC forecasting models flowchart.

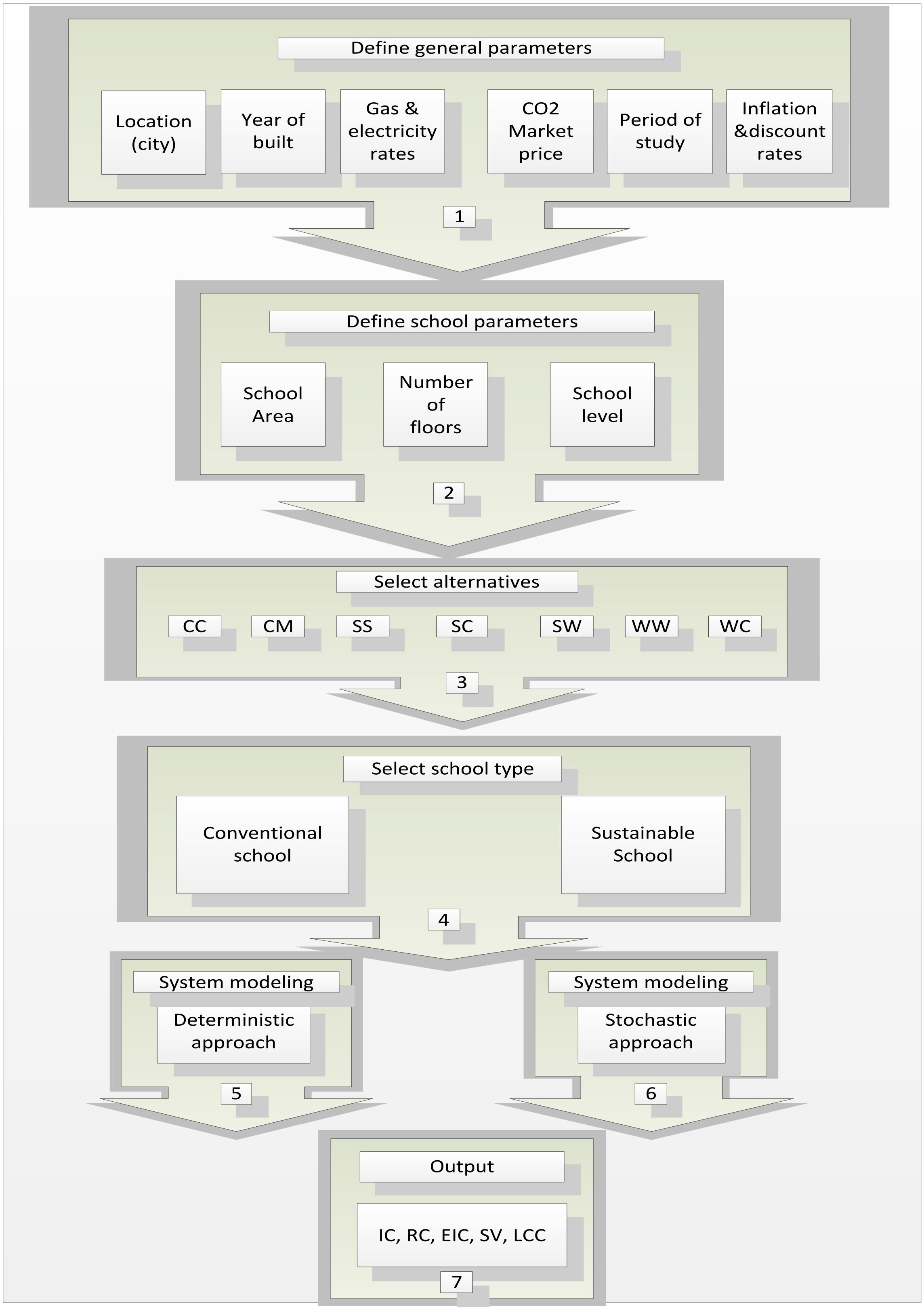


Figure 3.14 LCC Forecasting Models flowchart for School Buildings

LCC forecasting models are developed firstly through identifying of the general parameters such as city, year built, utility rates, period of LCC study, and inflation & discount rates. In this research, the case study is applied to be in the city of Montreal in 2011 whereas the utilities and other rates were identified accordingly. The second step is defining school parameters such as school area, level, and number of floor. These parameters are significant to compute the initial costs of conventional alternatives and the overall costs. Selecting of alternatives is the next step where all of them can be selected to be compared together. This step is correlated to the following step, which is identifying of school type whether conventional, sustainable, or both of them. The next step is to select the approach of forecasting, deterministic or probabilistic approach. Finally, the outputs are embodied in square footage and total costs of initial costs, running costs (energy, O&M, and major repairs), environmental impact costs, salvage values, and net present values as presented in Figure 3.14.

3.6 Applied Techniques and their Applications

3.6.1 LEED Rating Technique

The LEED rating technique was used in this research to measure the sustainability level that can be achieved by each structure and envelope type. There are three main categories in LEED that could be affected or governed by structure an exposure type, and these combine for a maximum total of 37 points. These categories include: energy and atmosphere (19 points), material and resources (13 points), and innovation and design process, which was represented by life cycle assessment (5points). A material and atmosphere checklist represents the energy reduction percent for such a building in a particular climate zone (zones 1-8), compared to the average baseline energy consumption of a conventional school that meets the minimum requirements of ASHRAE standard 90.1-2004.

Optimizing energy performance requires achieving of minimum of 2 points. These two points can be earned either when a reduction of 14% in energy consumption is provided in new construction, or when a reduction of 10% is achieved in existing-building renovation. The maximum of 19 points will be granted to those new buildings that achieve a reduction of 48%, compared to the minimum requirements of ASHRAE standard 90.1-2004. The other points that are offered for renewable energy were excluded here because they do not match with the scope of the conducted research. This category was tested by energy simulation software (eQUEST).

The second category is in materials and resources, which has the second highest number of points (13). This category contains the ability to recycle the building material, i.e. reuse and maintain structural and non-structural elements, diversion of material from the waste stream, and waste management. The data for this category was obtained through analysing of 109 existed LEED certified buildings that have various structure and envelope types.

Life-Cycle Assessment was incorporated with the LEED technique to measure the sustainability level that can be achieved by each structure and envelope type.

This technique is a representation of the innovation and design process, with five assigned points (5 points) as displayed in table 3.2.

Table 3.2 LEED Checklist for Schools (Green Building Council, 2009)

	Energy & Atmosphere		**19 Points**
Y	Prereq 1	**Fundamental Commissioning of the Building Energy Systems**	Required
Y	Prereq 2	**Minimum Energy Performance**	Required
Y	Prereq 3	**Fundamental Refrigerant Management**	Required
	Credit 1	**Optimize Energy Performance (2 pt minimum)**	2 to 1

12% New Buildings	1	14% New Buildings	2
16% New Buildings	3	18% New Buildings	4
20% New Buildings	5	22% New Buildings	6
24% New Buildings	7	26% New Buildings	8
28% New Buildings	9	30% New Buildings	10
32% New Buildings	11	34% New Buildings	12
36% New Buildings	13	38% New Buildings	14
40% New Buildings	15	42% New Buildings	16
44% New Buildings	17	46% New Buildings	18
48% New Buildings	19		

Excluded

	Materials & Resources		**13 Points**
Y	Prereq 1	**Storage & Collection of Recyclables**	Required
	Credit 1.1	**Building Reuse**, Maintain 75% of Existing Walls, Floors & Roof	1
	Credit 1.2	**Building Reuse**, Maintain 95% of Existing Walls, Floors & Roof	1
	Credit 1.3	**Building Reuse**, Maintain 50% of Interior Non-Structural Elements	1
	Credit 2.1	**Construction Waste Management**, Divert 50% from Disposal	1
	Credit 2.2	**Construction Waste Management**, Divert 75% from Disposal	1
	Credit 3.1	**Materials Reuse**, 5%	1
	Credit 3.2	**Materials Reuse**,10%	1
	Credit 4.1	**Recycled Content**, 10% (post-consumer + ½ pre-consumer)	1
	Credit 4.2	**Recycled Content**, 20% (post-consumer + ½ pre-consumer)	1
	Credit 5.1	**Regional Materials**, 10% Extracted, Processed & Manufactured Regionally	1
	Credit 5.2	**Regional Materials**, 20% Extracted, Processed & Manufactured Regionally	1
	Credit 6	**Rapidly Renewable Materials**	1
	Credit 7	**Certified Wood**	1

	Innovation & Design Process			**5 Points**
	Life Cycle Assessments LCA			
	Credit 1.1	**Innovation in Design:**	**Minimizing Embodied Energy**	1
	Credit 1.2	**Innovation in Design:**	**Minimizing Water Toxicity & Emissions**	1
	Credit 1.3	**Innovation in Design:**	**Minimizing Air Toxicity & Emissions**	1
	Credit 1.4	**Innovation in Design:**	**Minimizing Land Emissions**	1
	Credit 1.5	**Innovation in Design:**	**Minimizing Global Warming Potential**	1

Excluded

The first point was assigned for the minimum energy embodied overall life span. The second and third points were assigned for minimum water and air toxicity. The fourth point was assigned for minimum land emissions. The fifth point was granted to the option with minimum global warming potential. The total sustainability score was calculated by adding up the scores earned in each category for each structure and envelope type.

3.6.2 The Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a structured technique that is applied in complex decisions. The AHP assists decision makers in selecting the decision that best suits their requirements according to their understanding of the problem. The AHP provides a rational and comprehensive framework to structure a problem, represent and quantify its elements, connect the identified elements to goals, and to compare possible alternative solutions. (W. Contributors, 2009) Applying the AHP to a decision-making process begins by establishing the hierarchy structure of the problem through the building of the relationships of the goal, criteria, sub-criteria and alternatives, as shown in Figure 3.15. Once the hierarchy of a problem has been established, the decision makers evaluate and compare its different elements to each another. In making the comparisons, the decision makers can use their judgments about the elements or they can use real data, or a combination. The main attribute of the AHP is that human judgments, and not just the underlying information, can be used to perform the evaluations (Saaty, 2008). The AHP utilizes pair-wise comparison matrices consisting of various factors. The pair-wise comparison matrix provides the importance ratio for each pair of alternatives. Each matrix is a mutual matrix in which the main diagonal elements are 'one' and the values above the diagonal are mutual to those below. The relative importance of each category and sub category are based on a 1-9 scale with the interpretations as presented in Table 3.3. The AHP converts each different evaluation to numerical values that can be easily processed and compared over the whole range of the problem. A numerical weight is determined for each element of the hierarchy, which often permit incommensurable and varied elements to be compared to each other in a rational and consistent way – a feature that distinguishes the AHP from other techniques. Numerical priorities are estimated for each alternative in the final step of the process. These numbers represent the alternatives' relative ability to achieve the main goal, which allows a simple consideration of the various courses of action (Contributors, 2009)

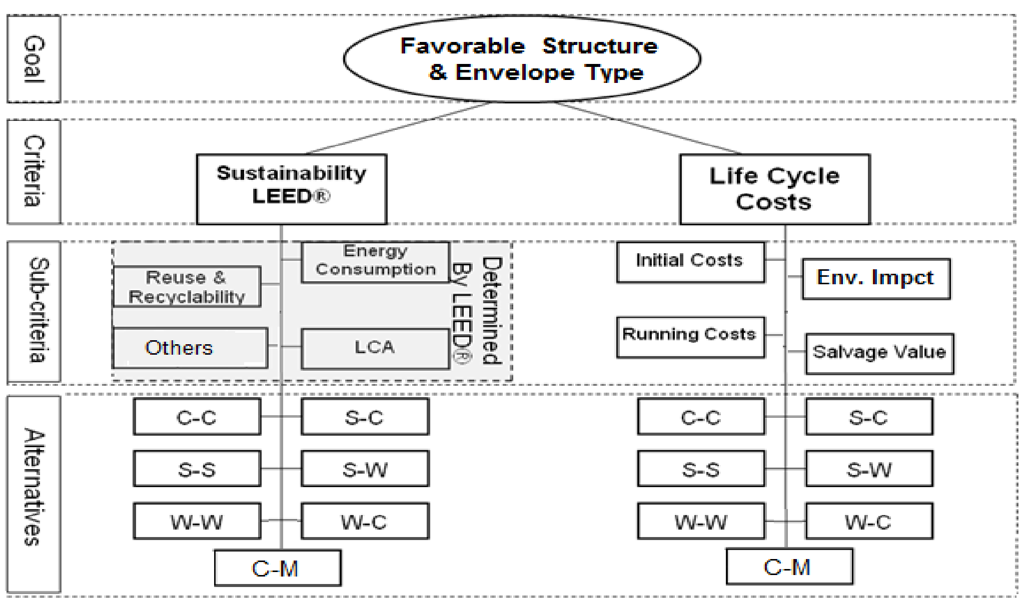


Figure 3.15 Analytical Hierarchy Process structure for this research

Table 3.3 Fundamental Scale for Pair-wise Comparisons (Saaty, 2008)

Verbal Judgment of preference	**Intensity of Importance**	**Explanation**
Equal Importance	**1**	Two elements contribute equally to the goal.
Moderate Importance	**3**	Experience and judgment slightly favour one element over another.
Strong Importance	**5**	Experience and judgment strongly favour one element over another.
Very Strong Importance	**7**	One element is favoured very strongly over another; its dominance is demonstrated in practice.
Extreme Importance	**9**	The evidence favouring one element over another is of the highest possible order of affirmation.
Intermediate Values	**2, 4, 6, and 8**	1.1, 1.2, 1.3 etc can be used for elements that are very close in importance.

3.6.2.1 Calculating AHP Weights

There are many techniques for calculating the AHP's final weights, but the Lambda max is the main technique applied in most research. This technique computes the weights of the criteria in the pair-wise comparisons. A vector of weights in this technique is the normalized eigenvector corresponding to Lambda max (the maximum eigenvalue) and is calculated from this equation (Saaty, 1980):

$$\mathbf{C} \times \mathbf{w} = \boldsymbol{\lambda} \times \mathbf{w} \qquad [3.1]$$

where:

- $\mathbf{C}$ is the pair-wise comparison matrix of the criteria,
- $\mathbf{w}$ is the weight vector, and
- λ is the maximum eigenvalue λ_{max}.

The mean of a normalized value is a simple method that is considered as an approximation to the Lambda max method, and is used to estimate the maximum eigenvalue. The pair-wise comparison matrix consistency ratio (C.R.) must be calculated to ensure the accuracy of the mean normalized value. A minimum consistency ratio means high accuracy, and can be calculated from Malczewski (1999):

$$C.R. = C.I / R.I \qquad [3.2]$$

where:

C.R. is the Consistency Ratio,
R.I. is the Random Consistency Index, and
C.I. is the Consistency Index **.**

The consistency index (C.I.) is illustrated as a degree of deviation from consistency. The consistency of each matrix is checked by computing its C.R. and C.I., which can be obtained from Han (1998):

$$C.I. = (\lambda_{max} - n) / (n - 1) \qquad [3.3]$$

where

n is the number of criteria, and
λ_{max} is the largest eigenvalue.

3.6.3 Multi Attribute Utility Theory (MAUT)

The Multi Attribute Utility Theory evaluation technique is suitable for complex decisions with many alternatives and multiple criteria. This technique is a quantitative comparison method applied to various criteria such as time, cost, safety and benefits, which have dissimilar measurement units along with different stakeholder and individual preferences, and turns these into high-level, cumulative preferences. Utility functions are the foundation of MAUT, which converts different criteria to one unified measurement scale identified as the multi-attribute “utility”. For example, the utility functions convert different attributes’ dimensioned scores such as dollars, pounds, feet, gallons per minute, etc. to a dimensionless utility score that varies between 0 and 1. Once utility functions are built, an alternative’s raw data -whether they are subjective or objective- can be transformed to unified utility scores (Baker, 2001). The various criteria are weighted based on their degree of importance, as with other techniques. Each decision criterion has a utility function created for it through the building of its own graph, which can be created based on the data for each criterion. The utility scores are weighted by multiplying the utility score by the weight of the decision criterion, which reflects the decision maker’s values and the experts’ opinion and is summed for each alternative. The preferred alternative is the one that reaches the highest score (Baker, 2001).

3.6.3.1 Attribute Utility Function

MAUT and utility functions are usually applied when the quantitative information for each alternative is determined, which can result in firmer measures of the alternative performances. Utility function is a value that calculates the quantitative value of an attribute’s worth, and it also measures risk. The determination of a small element (a single utility function) is required to perform the multi-attribute utility function. The single utility function could be graphically simulated, for example, as a decreasing function such as cost, or an increasing function such as quality. A utility function can be calculated from the following equation:

$$u\ (x_1, x_2, x_3, \ldots x_n) = f(u_1(x_1), u_2(x_2), \ldots u_n(x_n)) \quad [3.4]$$

where:

u(x) single attribute utility function.

3.6.3.2 Value Function

There are several methods which can be used to obtain a value function, but one of the most widely-applied methods is the bisection method (Goodwin, 2004). This method requires first determining the best or worst value or the highest and lowest value for each criterion, which can be obtained from collected data. The best value (the most-preferred value) was assigned a utility score of 1.0 while the worst value (the least-preferred value) was assigned a utility score of 0. The decision maker was then asked to identify a midpoint value function whose value is halfway between the least-preferred value and the most preferred one. The midpoint value was assigned a utility score of 0.5. Having identified the midpoint value, the decision maker was then asked to identify the ‘quarter point’, which has a value halfway between the least-preferred value and the midpoint one. The quarter point value was assigned a utility score of 0.25. Similarly, the decision maker was asked to identify value function (utility score of 0.75) which has a value halfway between the midpoint and the best (most preferred) value. When the decision maker determined these five value points, plotting the value function or attribute utility graph was done accordingly (Goodwin, 2004).

3.6.3.3 Attribute Utility Graphs

Experts' and decision makers' opinions govern the plot of the value function or the shape of a utility graph. The plot can be linear, or show fluctuation, be zigzag or a concave or convex curve based on the nature of the criteria and the experts' opinion. In this study there are five different attribute utility graphs: initial costs, running costs, Environmental impact costs, salvage values, and sustainability (LEED point's graph). The sustainability utility graph has already been created for this study because the clear linear correspondence between LEED points and utility scores can be seen in Figure 3.16. The other utility functions were identified, according to experts' and decision makers' opinions.

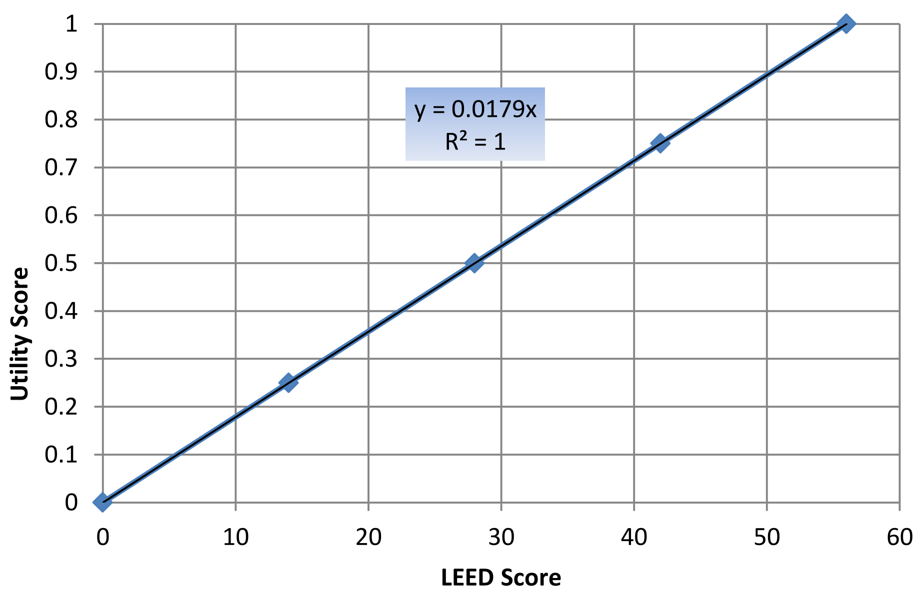


Figure 3.16 Utility Function Graph for LEED points

3.6.4 Linear Regression

Regression analysis is a statistical methodology that utilizes the relation between two or more quantitative variables so that a response or outcome variable can be predicted from the other, or others (Neter, 1996). Regression analysis involves analyzing and modeling techniques for several variables, focusing on finding a correlation between a dependent variable and one or more independent variables. In other words, regression analysis helps investigators to know the adjustments that have to be made to the value of the dependent variable if any independent variable is modified, while keeping the other independent variables fixed. This analysis mainly computes the conditional expectation of the dependent variable (average value of the dependent variable) given the independent variables. The main objective of this technique is to estimate a function of the independent variables, known as a regression function. A regression model relates Y to a function of X and β according to (W Contributors, 2010) as follows:

$$Y = f(X, \beta) \qquad [3.5]$$

where:

- β is the unknown parameter,
- X is the independent variable., and
- Y is the dependent variable

3.6.4.1 Overview of the Steps in Regression Analysis

It is essential that the conditions of the regression model be appropriate for the data at hand in order for the model to be applicable. The typical strategy for regression analysis can be described in the following steps (Neter, 1996). The first step is an exploratory study of the data, as shown in the flowchart in Figure 3.17. On the basis of this initial exploratory analysis, one or more preliminary regression models are developed. These regression models are then examined as to their appropriateness for the data at hand, and they will be revised, or new models developed, until the investigator is satisfied with the suitability of a particular regression model (Neter, 1996).

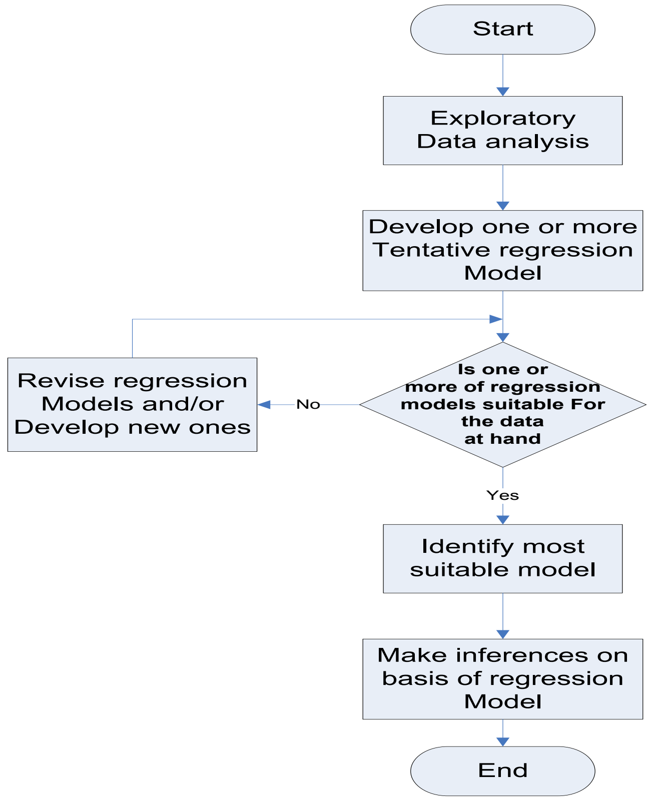


Figure 3.17 Typical Strategies for Regression Analysis (Neter, 1996)

In regression analysis, it is also of interest to characterize the variation of the dependent variable around the regression function, which can be described by a probability distribution (W Contributors, 2010). R-square value is a significant estimation that should be performed along with regression analysis. It is also called the coefficient of determination, defined as the ratio of the sum of squares explained by a regression model and the "total" sum of squares around the mean (Henry, 2001). This value can be estimated by:

$$R = 1 - SSE / SST \quad [3.6]$$

Where **SSE** = error sum of squares, and **SST** = total sum of squares

When the R-square is high, i.e., close to 1.00, that indicates a good estimate. The estimated cost would be a very poor estimate if the R-square were only .01, since that means the data does not fit on the regression line at all (Weisberg, 2002).

3.6.5 Monte Carlo Simulation

Monte Carlo sampling techniques are totally random therefore any given sample could fall within the range of the input distribution. Monte Carlo techniques are applicable to a wide range of complex problems involving random behavior. A wide range of algorithms are available for generating random samples from different types of probabilities distributions (Shahata, 2006). Monte Carlo simulation sample uses a new random number between 0 and 1. Monte Carlo simulation technique results in the probability distribution for the LCC components and NPV, from which one can obtain meaningful estimates of median (50-percent confidence level), 70^{th} percentile, and 95^{th} percentile (95-percent confidence level) and other relevant quantities. The Monte Carlo simulation technique was applied in this study as the following steps:

1- A probability distribution function is defined for all uncertain parameters (e.g. Life Cycle Components costs, discount rate, and inflation rates)
2- Monte Carlo simulation begins generating random numbers ranges from 0.0 -1.0.

3- Random numbers are then used to enter the predefined cumulative probability distribution to get the random values for the uncertain parameters.

4- This process was repeated several times to establish a probability distribution function for the output life cycle cost elements. To perform the previous simulation steps the Crystal ball® 2011 software was utilized in this research.

3.6.6 Risk Assessment (Efficient Frontier)

Efficient Frontier analysis is a powerful portfolio optimizer technique that was developed based on key concepts of modern portfolio theory. This technique analyzes trade-offs between expected return and associate risk of different alternatives composed of different asset weightings. Changing weightings of asset will influence both the expected risk and expected return (measured by standard deviation) of the alternative. The Efficient Frontier technique analyzes all possible alternatives through varying asset weights and determines the ones that obtain the highest expected return at a certain level of risk (Invstorcraft, 2011). These alternatives should be plotted on a curve called the Efficient Frontier. The Efficient Frontier curve corresponds to the most efficient investment strategies. Any given alternative on the Efficient Frontier is said to dominate all other possible alternatives that have either the same level of standard deviation or expected return. Figure 3.18 displays the plotted curve of Efficient Frontier analysis for various alternatives. After plotting the Efficient Frontier curve, the technique then determines the attractive or optimum alternative (Invstorcraft 2011). It does this by selecting the alternative that falls at the point of tangency with the straight line starting at the risk-free rate of return on the y-axis as can be seen in Figure 3.18.

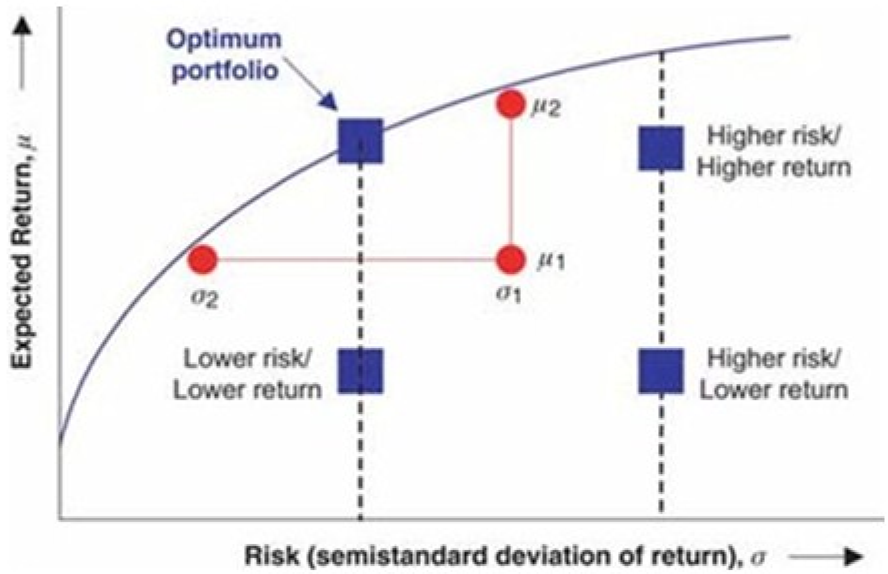


Figure 3.18 Efficient Frontier Technique (Mhj3.com 2011)

In this research Efficient Frontier analysis was applied to enhance the analysis of the selection framework output where no benefit or return is expected. Efficient Frontier analysis calculates the curve that plots an objective value (Means of project unit cost) against changes to probabilistic constraints (standard deviation of the project unit cost). This analysis allows comparisons of project mean costs against different levels of risk to enable decision makers in school boards of making well informed decisions. The alternative with minimum costs mean and standard deviation was selected as attractive one.

3.6.7 Sensitivity Analysis

Sensitivity analysis is a technique that is applied to measure how sensitive a model is to changes in the value of its parameters and to its structure. Parameter sensitivity is often performed as a series of tests in which the modeller sets various parameter values to see how a change in a parameter causes a change in the model. By showing how the model behaviour responds to changes in parameter values, sensitivity analysis is a useful tool in model building as well as in model evaluation. Sensitivity analysis helps to build confidence in the model by studying the uncertainties that are often associated with model parameters. In system dynamics models, many parameters represent quantities that are very difficult, or even impossible to measure to a large degree of accuracy in the real world. Also, some parameter values do change in the real world (Breierova and Choudhari, 2001).

3.7 Utilized Tools and their applications in this study

3.7.1 Energy Simulation Software (eQUEST)

eQUEST is an energy simulation and analysis tool that ensures high quality results by incorporating an energy efficiency measure (EEM) wizard, a building creation wizard. This software creates graphical results that display modules with an enhanced DOE-2.2-derived building energy use simulation program. The building creation wizard guides a designer and users throughout the process of creating a building model. DOE-2.2 is the engine of the software that performs an hourly simulation of the building performance based on many inputs such as people, plug loads, ventilation, wall layers, and windows. It also shows the performance of chillers, boilers, fans, pumps, and other equipment. eQUEST enables users to perform multiple simulations and to compare the alternative results in side-by-side graphics. It provides energy cost estimation and automatic implementation of energy efficient measures to help select the most preferred choice (Crawley et al., 2005).

3.7.2 Life-Cycle Assessment Software (ATHENA)

ATHENA is a building impact assessment estimator software based on life-cycle assessment, developed by the Athena Institute in Canada, which is a non-profit organization whose goal is to improve the sustainability of buildings through the implementation of the LCA technique. “ATHENA Impact Estimator for Buildings is the only software tool in North America that evaluates whole buildings and assemblies based on LCA methodology” (The Athena Institute, 2011). ATHENA software is considered to be an LCA tool that focuses on the assessment of building assemblies such as floors, walls, roofs or whole building systems and components. The software enables architects to assess and compare in advance the environmental implications of designs, whether for new buildings or for major renovations. This tool incorporates ATHENA’s databases that cover many of the building exposure systems and structure types that are typically used in commercial and residential buildings. Athena software assists users to describe their building architecturally, and then provides LCA-based environmental comparisons of alternative designs and materials. ATHENA was created to be utilized at the conceptual design stage, and a summary without weighting is provided for global warming potential, embodied energy usage, pollutants to water, solid waste emissions, pollutants to air, and natural resources use. The evaluation and comparison dialogue feature permits the side-by-side comparison of several alternative designs. The ATHENA output provides region-specific results of design and does this for cradle-to-grave (Kibert, 2005).

CHAPTER 4: DATA COLLECTION

4.1 Introduction

Data was collected and analyzed for this research via several methods and techniques. Each method was designed for a certain purpose and yields information with a specific context. The selection of data collection methods and analysis techniques depends on the type of data required and the reason why it is required. The techniques include: literature review, questionnaires and surveys, interviews, consulting by phone and by email, data review, and review of other published data. The main sources of data collection in this research include: American and Canadian school districts and boards, Statistics Canada, US and Canadian Green Building Councils, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), RSMeans, Advanced Energy Design Guide for K-12 School Buildings, the Canadian Institute of Steel Construction, the Canadian Wood Council, the Canadian Ready-Mixed Concrete Association (CRMCA), real estate agents, contractors, owners, decision makers and experts, and school building users.

4.2 Data Collection of LCC Components

An integrated database was developed to enable school boards to predict life cycle costs for their new school buildings in order to select the most attractive alternative. LCC components include: initial costs, running costs such as operating and maintenance costs, energy costs, major repairs or asset renewals, environmental impact costs, salvage value, and discount and inflation rates. Each LCC data component has several methods for collecting and is gathered from different resources, as shown in Figure 4.1.

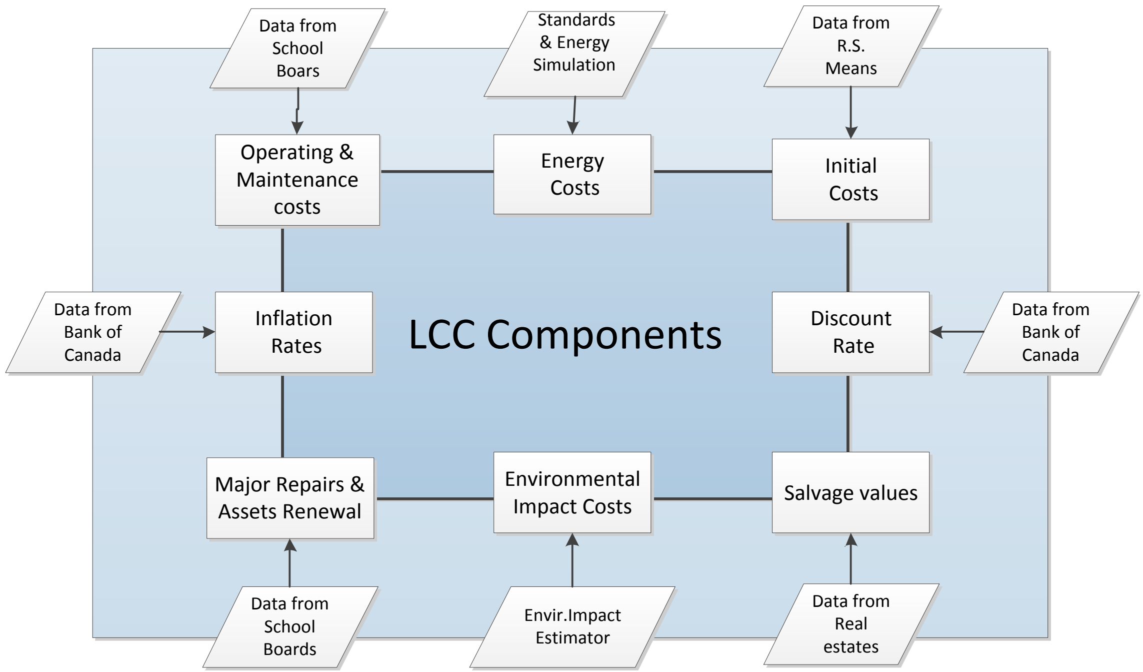


Figure 4.1 Data collection method and resources for LCC components

4.3 LCC Components for Conventional School Buildings

4.3.1 Initial Costs (Construction Costs)

The initial costs for a conventional school building were calculated using the RSMeans Construction Cost calculator (2011), which provides a square footage cost data for various building types. RS Means publishes construction cost data and offers consulting based on their record of collecting data from all facets of the industry in North America. Their estimates represent the national average probable costs developed by their engineering staff, assuming average quality materials and typical construction methods. The RSMeans square foot cost is developed as a standard to be applied at the early phases of projects for budgeting purposes when the complete design of a project is not yet fully realized. The RSMeans model estimates the cost based on the occupancy of building along with the physical characteristics, since occupancy alone does not always best identify the building construction type. This model requires the identification of some parameters such as school level, number of floors, structure and envelope type, location (city), floor height, school area, labour type, and year of construction. The total cost or the total square foot cost is the result of the cost estimate of the substructure, structure and envelope, interiors, services, equipment and furniture, contractor fees, and architecture fees, as shown in table 4.1

Table 4.1 Total square foot cost estimate (RS Means, 2011)

Square Foot Cost Estimate Report

Estimate Name:	Untitled
Building Type:	School, High, 2-3 Story with Face Brick with Concrete Block Back-up / R/Conc. Frame
Location:	MONTREAL, PQ
Story Count:	2
Story Height (L.F.):	13
Floor Area (S.F.):	175000
Labor Type:	Union
Basement Included:	No
Data Release:	Year 2011
Cost Per Square Foot:	$152.40
Building Cost:	$26,668,500

Costs are derived from a building model with basic components.
Scope differences and market conditions can cause costs to vary significantly.

Item	% of Total	Cost Per S.F.	Cost
A Substructure	4.70%	$5.30	$928,000
B Shell	32.10%	$36.55	$6,396,500
C Interiors	21.50%	$24.51	$4,290,000
D Services	38.80%	$44.17	$7,729,500
E Equipment & Furnishings	3.00%	$3.40	$595,000
F Special Construction	0.00%	$0.00	$0
G Building Sitework	0.00%	$0.00	$0
SubTotal	100%	$113.94	$19,939,000
Contractor Fees (General Conditions,Overhead,Profit)	25.00%	$28.49	$4,985,000
Architectural Fees	7.00%	$9.97	$1,744,500
User Fees	0.00%	$0.00	$0
Total Building Cost		$152.40	$26,668,500

4.3.2 Energy Costs

Energy costs are calculated in this research according to the current prices of electricity and natural gas in the city of Montreal. These rates include the average prices that are provided from the government of Quebec to the provinces' school buildings. The electricity rate is provided by Hydro Quebec and computed in kW/h, while the natural gas price is provided by Gaz Metro and calculated in cubic meter (m^3). Energy consumption is simulated and measured initially and then the total energy costs per square foot are computed accordingly.

4.3.2.1 Prototype Models' Characteristics

The prototype models' characteristics are developed for elementary and high school buildings by applying the criteria and recommendations in ASHRAE 90.1 and ASHRAE 62 (2004). The average school area of the tested models is referenced to a survey conducted on American schools and universities and to a school planning and management survey, which document both the average area and the number of students in elementary and high schools (ASU 2006, SPM 2007). The average area for elementary schools ranges from 73,000 ft^2 to 80,000 ft^2 (6,782 m^2 to 7,432 m^2), for 700 to 725 students. The capacity of the modeled school prototype is about 700 students with an average of 107.1 ft^2/ student, which represents the average of the ASU and SPM surveys. Classrooms in elementary school buildings represent the major area with about 50% out of the total school area as shown in table 4.2.

The capacity of the modeled high school prototype is about 1500 students, with an average numbers of 166.7ft²/student in accordance with the average provided by the ASU survey. Classrooms in high school buildings represent the major component, occupying about 45% of the total school area as shown in table 4.2. The remaining 55% includes the corridors, dining area, offices, lobbies, kitchen, library, auditorium, exercise center (gym), and restrooms.

Thermal zones in school buildings are classified according to the function of the space as well as the occupancy, as they are affected by the number of occupants, type of occupancy, and the required level of services such as the equipment loads and required lighting level(s).

Table 4.2 Total space sizes in elementary and high schools

Space Type	Elementary		High	
	% of Area	Total Area	% of Area	Total Area
Classrooms	50%	37500	45%	112500
Corridors & lobby	15%	11250	10%	25000
Exercise centre	10%	7500	10%	25000
Dining Area	5%	3750	10%	25000
Kitchens	5%	3750	5%	12500
Library	5%	3750	5%	12500
Auditorium	5%	3750	10%	25000
Restrooms	5%	3750	5%	12500
Total	100%	75,000	100%	250,000

A building operation time schedule is a very significant input that needs to be determined so that realistic hourly energy simulations can be performed. Since the analysis is applied to school buildings in Montreal, located in climate zone 6A, the operation time schedule was collected from school boards in Montreal for the calendar year 2011. The annual operation time schedule for schools in Montreal consists of three main periods starting on the 7th of January and ending the 22nd of December, with daily occupied times starting from 8 am to 4 pm as shown in Table 4.3.

Table 4.3 School building operation time schedule (Montreal school boards)

Opens at	End at	Occupied Time
Friday , JAN 07	Sunday, FEB 27	8 AM – 4 PM
Tuesday, MAR 08	Thursday, JUN 30	
Thursday, AUG 25	Thursday, DEC 22	

4.3.2.2 Internal Energy Loads

Internal loads include the heat generated from occupants, equipment, lights, and appliances. A plug load is any electrical device that is plugged into the outlets in a school and that is used continuously or periodically during the school year. Plug loads include TVs, printers, computers, copiers, appliances such as beverage and vending machines, and any devices that have or need a wall cubic (transformer) to operate (Pless et al., 2007).

Table 4.4 Elementary school internal loads by space type

Space Type	Maximum occupants (#/1000ft²)	Lighting power Density (W/ft²)	Peak Equipment Load (W/ft²)	Design Ventilation (CFM/person)
Classrooms	25	1.4	1.4	7.60
Corridors & lobby	5	0.5	0.4	15.00
Exercise centre	30	1.4	0.5	7.50
Dining Area	100	0.9	1.0	7.46
Kitchens	15	1.2	1.9	30.00
Library	25	1.2	1.4	15.00
Auditorium	30	1.4	0.5	7.48
Restrooms	10	0.9	0.5	15.00
Weighted Average for Elementary	30	1.11	0.95	13.13

The load intensity for the occupancy loads refers to the maximum occupancy at the peak time of a typical day. Plug loads and lighting are represented by peak power density in watts per square foot. Equipment loads include all loads not associated with HVAC, service water heating, and lighting. In addition to all loads that are plugged in, equipment load also includes items such as elevators, distribution transformer losses, cooking appliances, and kitchen refrigerators (Pless et al., 2007).

Table 4.5 High school internal loads by space type

Space Type	Maximum occupants (#/1000ft²)	Lighting power Density (W/ft²)	Peak Equipment Load (W/ft²)	Design Ventilation (CFM/per)
Classrooms	25	1.4	0.9	7.60
Corridors & lobby	5	0.5	0.4	15.00
Exercise centre	100	1.4	0.5	7.50
Dining Area	100	0.9	1.0	7.46
Kitchens	15	1.2	1.9	30.00
Library	25	1.2	1.4	15.00
Auditorium	100	1.4	0.5	7.48
Restrooms	10	0.9	0.4	15.00
Weighted Average for High school	47.5	1.11	0.87	13.13

Occupancy loads are based on default occupant density (ASHRAE 2004). The ASHRAE 90.1-2004 LPDs, peak occupancy, design ventilation, and peak plug loads for elementary school buildings are shown in Table 4.4 (Pless et al., 2007). The average of peak plug loads for elementary school buildings is 0.95 w/ft², where the average of the maximum occupants is 30 occupants/1000ft². In high school buildings, the average peak equipment load is 0.87 w/ ft² with the average of the maximum occupants being 47.5 occupants/1000ft², as shown in table 4.5. The average lighting power density is equal for elementary and high school buildings (1.11 w/ft²), and the ventilation average in both school levels is about 13.13 CFM/person.

Other inputs, such as occupancy description, space conditions, heating and cooling systems, and year of analysis are described in advance to allow for a complete energy simulation. These other parameters are identified according to the recommendation of ASHRAE 90.1(2004) and ASHRAE 62 (2007) and include the thermal properties of windows, solar heat gain coefficient, infiltration of the exterior wall area and of the floor area, as shown in Table 4.6.

Table 4.6 Characteristics of other inputted energy parameters

Items	Description
Occupancy	Fully occupied during school hours, partially year round
Percent conditioned	Fully heated and cooled
Thermal transmittance of window	U – (0.42) (btu/h-ft-°F)
Solar heat gain coefficient	(SHGC)-0.40 (btu/h-ft-°F)
Infiltration Ext wall area (perimeter)	0.038 CFM/ ft²
Infiltration floor area (core)	0.001 CFM/ ft²
Heating equipment	Hot water coils
Cooling equipment	Chilled water coils
Analysis year	2011
Code	ASHRAE 90.1, ASHRAE 62

4.3.3 Operating and Maintenance Costs

The operating and maintenance cost data are gathered from the Lester B. Pearson School Board in Montreal (LBPSB, 2011). This data includes the national average square footage costs for school buildings in the province of

Quebec. These costs include operating costs such as cleaning, maintenance, utilities (water, phones), and other O&M costs.

Cleaning costs include labour, contractors, cleaning equipment, repairs to cleaning equipment, mops, miscellaneous tools, hand drying paper etc.

Maintenance costs include labour, plumbers, electricians, locksmiths, mechanical work, technicians, carpenters, painters …etc

Other costs include management staffs at the school board level who oversee the school building plant.

4.3.3 Major Repair Costs

Major repair (MR) cost data was gathered from a number of school boards and districts in New York state school districts and in the Los Angeles school district. These costs are virtual annual costs that needed to be reserved and spent after decades of continuous operation. This data is historical information about expenses that occurred during different time periods and is transferred to current values in order to be used in the developed LCC forecasting model.

The scope of the major repair cost data covers a large sample that contains more than 400 conventional elementary and high school buildings located in more than 140 cities in California and in New York. The MR data includes information on 140 wooden school buildings in Los Angeles, and 130 steel plus 140 concrete school buildings in New York State. The data was obtained from the existing buildings' condition surveys, distributed by the inspection departments in their respective school districts to quantify the major repairs costs for their school buildings. These surveys include detailed information about school buildings, such as the name of school district, building name, address, the inspection date, year of construction, size (area), and the number of floors, as shown in Table 4.7.

Table 4.7 Major repairs' collected data - building description (NYSD, 2005)

Building Condition Survey Instrument

Part 1 of 6 * = Required Field

Name of School District *: ALBANY CITY SD

BEDS District Code *: 01010001

Building Name *: Arbor Hill Elementary School

SED Control Number (Bldg ID)*: 0047 Survey Inspection Date *: 11/10/2005

Use Building's 911 Address for Questions 6 to 8

Street *: Lark Drive

City *: Albany

Zip Code (Plus Four)*: 12204 - Certificate Expiration Date *: 6/1/2006

Certificate of Occupancy Status (A - Annual, T - Temporary, N - None) A

<u>Building Age and Gross Square Footage (GSF)</u>

Year of Original Building * 1973 GSF of Building as Currently Configured * 192300 No. of Floors *: 3

The data includes a description of each building's structure and envelope type, such as structural floors, columns, exterior walls, and roof. The data also contain some significant information such as the overall condition of the inspected item(s), the year of the most recent major repairs, and the expected remaining useful life, as shown in Table 4.8.

Table 4.8 Major repairs collected data – structure & exposure type (NYSD, 2005)

The MR data also indicates detailed information about the current major repairs, MRs that are planned, descriptions of major repairs and the date of completion of previous works, the actual start date of current works and their planned completion date(s), and the costs of previous and planned works, as indicated in Table 4.9.

Table 4.9 Major repairs description and their costs (LASD, 2011)

Projects Underway

Program	Proj #	Description	Actual Start Date	Planned Completion	Current Budget
FSU	1ZEF1-1	FIRE ALARM SYSTEM	07/31/2009	02/03/2012	$124,792
D_M	1ZNX1-1	INTERIOR PAINTING & REFINISH	06/16/2011	09/01/2011	$36,285
RRGM	M9299-1	REMOVE AND REPLACE CEILINGS IN SUPPORT OF INTERIOR PAINT	03/25/2011	09/30/2011	$65,580
RRGM	M9300-1	PRE-PAINT INTERIOR REPAIRS	03/25/2011	09/30/2011	$10,120
Subtotal for "Projects Underway" (4 Projects)					$236,777

Completed Projects

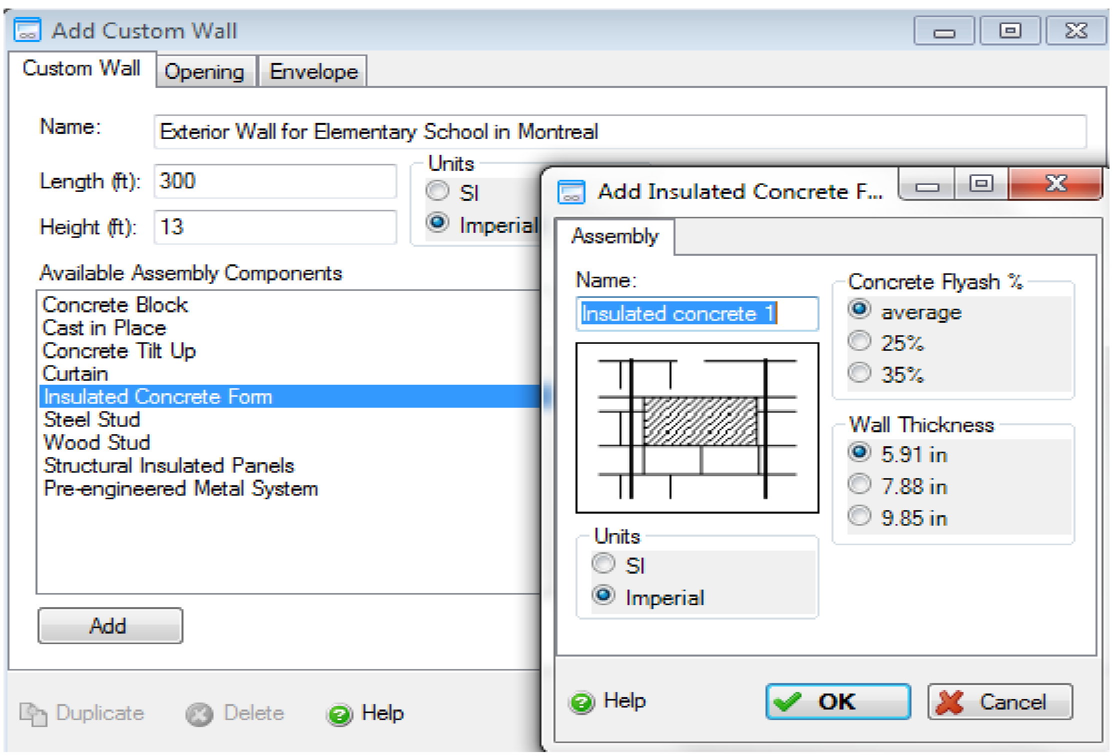
Program	Proj #	Description	Completed Date	Current Budget
BB	00705-1	CONSTR - PAINT EXTERIOR AND MASONRY/STUCCO	05/07/1998	$331
BB	05125-1	CONSTR - PAINT ALL CLASSROOMS	02/27/1998	$20,620
D_M	1ZNV7-1	EXTERIOR PAINTING & REFINISH	03/15/2011	$28,455
D_M	1ZXS5-1	EXTERIOR PRE-PAINT REPAIRS	02/11/2011	$36,788
SRU	202Q6-1	JOC CONST : PORTABLES - SEISMIC RETROFIT	08/08/2007	$38,209
R	285Q7-1	CONST : CCTV, IRRIGATION, LUNCH TABLES	05/06/2008	$93,535
K	373Q0-1	CONSTR - New Public Address System	05/15/2006	$41,297
K	839Q0-1	CONST : REROOF BUILDING(S)	09/21/2006	$23,891
BB	8930H-1	CONSTR - CLSRMS, SAFETY & TECH.	04/24/2000	$179,227
BB	8930I-1	CONSTR - LOCALLY DETERMINED NEEDS	04/14/2006	$370
BB	8930K-1	CONSTR - SECURITY GRILLS - GROUND LEVEL WINDOWS	08/15/1998	$2,816
D_M	M7669-1	CONST : REM & RPL ROOFTOP A/C UNITS	02/28/2008	$97,819
BB	R0483-1	CONSTR - REPLACE FLOORING	07/25/2002	$12,080
BB	R0483-2	CONSTR - ASBESTOS ABATEMENT OF DETERIORATED FLOOR COVERING	07/25/2002	$6,644
Subtotal for "Completed Projects" (14 Projects)				$582,082

Time adjustment factors were collected from RS Means to convert the historical cost data from different times to 2011, to make it possible to distribute it on LCC forecasting cash flows. In addition, city adjustment factors were gathered for commercial buildings from RS Means to adjust the collected cost data from various locations in North America to the city of Montreal.

4.3.4 Environmental Impact Costs

ATHENA Impact Estimator for buildings is the software tool used in this study to evaluate building structures, envelopes, and assemblies based on LCA methodology. This software contains a huge database that is utilized to measure the environmental impact associated with various structure and envelope types, as illustrated in Table 4.10. In addition, operation data such as electricity and gas consumption is gathered by performed energy simulations in order to implement LCA from the manufacturing to the demolishing phases of a building's life.

Table 4.10 Wall types in the ATHENA database



The cost of carbon dioxide is collected from the Carbon Market News provided by the PointCarbon website (Pointcarbon, 2011).

4.3.5 Salvage Value

Salvage value data is collected from the RSMeans Facilities Maintenance Standards, which proposes the average useful life of building components. Each structure and envelope type has a specific average useful life based on historical data. Some examples are shown in Table 4.11.

Table 4.11 Suggested average useful life of building components (Means, 2009)

Item	Years	Item	Years
I. Major Construction		b. Fire Pumps	20
A. Reinforced Concrete Frame		c. Hose Housings	
1. Masonry Exterior		1) Wood	15
a. Heavy	45	2) Steel	20
b. Light & Medium	40	3) Masonry	30
B. Steel Frame		5. Sump Pumps	
1. Masonry Exterior		a. Small	10
a. Heavy	45	b. Large	15
b. Medium	35	6. Water Heaters — gas & electric	10
c. Light	30	7. Water Wells	25
2. Metal Exterior		D. Service Systems	
a. Heavy	45	1. Elevators (all types)	20
b. Medium	35	2. Fire Alarm	20
c. Light	30	3. Intercom	15
C. Wood Frame		4. Telephone	15
1. Masonry Exterior		**III. Miscellaneous Items**	
a. Heavy	35	A. Bulkheads	
b. Medium	25	1. Concrete	30
2. Metal Exterior		2. Steel	25
a. Heavy	30	3. Timber	20
b. Medium	25	B. Chimneys	
c. Light	20	1. Brick or concrete	35
3. Wood Exterior		2. Steel-lined	25
a. Heavy	25	3. Steel-unlined	20
b. Light & Medium	20	C. Culverts	

Salvage value data was collected from real estate publications in North America to determine the depreciation methods for educational and commercial facilities. The straight line depreciation method is applied based on the expected useful life of schools.

4.3.6 Measuring Sustainability of Conventional School Buildings

The Leadership in Energy and Environmental Design (LEED) certification system is used to measure the sustainability level of conventional school buildings. The data is gathered from the LEED checklist for school buildings to measure three categories of the LEED® rating system: energy and atmosphere, material and resources, and innovation & design process. Each LEED category requires various sorts of data and utilizes different methods of data collection.

4.3.6.1 Energy and Atmosphere

eQUEST 3.46 (2010) software is used to measure the energy performance of the various envelope types. School prototype energy loads and the other inputs are defined based on the Energy Design Guide for K-12 School Buildings in North America (AEDG, 2008). This guide is a benchmark developed using the ANSI/IESNA/ASHRAE Standard 90.1-1999 to build new schools that are 30% more energy efficient than current industry standards. The design of the fenestration, lighting systems, HVAC systems, building automation and controls, outside air treatment, and water heating are specified based on the K-12 AEDG (2008) recommendations for climate zone 6a. These recommendations are specifically designed for the various structure and envelope systems such as floors, roofs, exterior walls, and openings. For instance, K-12 AEDG contain the recommendations of exterior wall insulations, comprising the typical wall types such as the mass wall, steel framed, wooden framed, and metal buildings, as shown in Table 4.12. The K-12 AEDG recommendations are applied to energy simulations with the goal of achieving high energy savings.

Table 4.12 K-12 AEDG recommendations for climate zone 6a

	Item	Component	Recommendation
Envelope	**Roofs**	Insulation entirely above deck	R-25 c.i.
		Attic and other	R-38
		Metal building	R-13 + R-19
	Walls	Mass (HC > 7 Btu/ft2·°F)	R-13.3 c.i.
		Steel framed	R-13 + R-7.5 c.i.
		Wood framed and other	R-13 + R-7.5 c.i.
		Metal building	R-19 + R-5.6 c.i.
	Floors	Mass	R-13.3 c.i
		Steel framed	R-30
		Wood framed and other	R-30
	Vertical Fenestration	Total fenestration to gross wall area ratio	35% max
		Thermal transmittance—all types and orientations	U-0.42
		SHGC—all types and orientations	SHGC-0.40
Lighting	**Interior Lighting**	Classroom daylighting (daylighting fenestration to floor area ratio)	Sidelighted South-facing: 8%–11% North-facing: 15%–20%
			Combined toplighted and sidelighted— South-facing sidelighted: 6%–8%, Toplighted: 2%–3% North-facing sidelighted: 9%–13%, Toplighted: 3%–5%
		LPD	1.2 W/ft2 maximum
		Light source system efficacy	50 mean lm/W minimum
		Occupancy controls—	general Manual on, auto off all zones
HVAC	**Packaged DX Rooftops (or DX Split Systems)**	Air conditioner (<65 kBtu/h)	13.0 SEER
		Air conditioner (≥65 and <250 kBtu/h)	Comply with Standard 90.1*
		Heat pump (<65 kBtu/h)	13.0 SEER/7.7 HPSF
		Gas furnace (<225 kBtu/h) Gas	80% AFUE or Et
		furnace (≥225 kBtu/h)	80% Ec
		Economizer	>54 kBtu/h
		Ventilation	Energy recovery or demand control
		Fans	Constant volume: 1 hp/1000 cfm Variable volume: 1.3 hp/1000 cfm

4.3.6.2 Material and Resources

The material and resources category includes the reuse of major structural components, the recyclability of content, the amount of construction waste that can be diverted from landfills, the use of regional materials and of rapidly renewable materials.

The data for this category was collected for a large--scale sample that consists of more than 110 LEED-certified school buildings in the United Stated and Canada. Each LEED certified building is classified according to its structure and envelope type and then the LEED scores associated are computed individually for each building. Finally, the average LEED score is estimated for each structure and envelope type to distinguish which alternative can achieve the highest LEED score.

Most of the data gathered for this category is from the Green Building Council, (USGBC, 2010) and other websites such as schools' websites or the journal articles in the field.

4.3.6.3 Innovation and Design (LCA)

Life Cycle Assessment is performed utilizing the ATHENA's database to define building components such as foundations, slabs on grades, walls, columns, beams, floors, roofs, openings and other material. This database covers many of the building exposure systems and structure types that are typically used in school buildings.

4.4 LCC Components for Sustainable School Buildings

Since the LEED rating system is considered a benchmark of sustainability, LEED certified school buildings have become popularized in the media. There are about 200 new LEED-certified school buildings in North America classified as sustainable or green school buildings. A large data sample (from 142 LEED-rated school buildings) was collected and investigated in this research to measure the economic viability of sustainable school buildings. The LEED certified school building data was gathered initially from the US Green Building Council (USGBC, 2010). That data was limited and only includes a portion of the significant information required for the development of an LCC model, such as school name, school level, location (city and state), year of construction, and LEED score and certification level, as shown in Table 4.13.

Table 4.13 Data Sample of LEED-certified school buildings (USGBC, 2010)

School Name & Level	Location (City)	State	Certification Level	Year of Built	LEED Score	Total Building Gross Area (ft^2)
The Dalles High School	Dalles	OR	Gold	2000	39	96,500.00
Third Creek Elementary School	Statesville	NC	Gold	2000	39	92,000.00
Clearview Elementary School	Hanover	PA	Gold	2001	42	43,453.00
IslandWood: A School in the Woods	Bainbridge Is.	WA	Gold	2001	40	16,300.00
Wrightsville Elementary School	Wrightsville	PA	Silver	2001	34	80,400.00
Clackamas High School	Clackamas	OR	Silver	2001	33	265,355.00
Willow School Phase I	Gladstone	NJ	Gold	2001	39	15,372.00
FHPS New Secondary Building	Grand Rapids	MI	Certified	2001	27	214,000.00
West Ottawa Public Schools	Holland	ON	Certified	2003	26	245,000.00

The remaining vital data was collected individually for each LEED-certified school building from various resources in order to build a comprehensive database for an LCC forecasting model for sustainable school buildings. This data was gathered for the complete sample of 142 sustainable school buildings from articles, school websites, websites and articles. This data includes the significant information that is not included in the US Green Building Council such as structure and envelope type, number and type of floors, initial costs, energy savings, water savings, operating and maintenance costs, major repair costs, salvage value, and environmental impact costs.

- The initial costs (construction costs) were gathered from the green building's articles, schools' websites, and other websites.
- Energy and water consumption was collected from articles and the green building council website.
- Operating and maintenance cost data was collected from a green building study guide which was derived from conventional school building data.
- Salvage values were collected from the RSMeans Facilities Maintenance Standards and real estate websites.
- Environmental impact and carbon dioxide emissions data was gathered from articles and the price of carbon dioxide emissions were gathered from the carbon market (pointcarbon website).
- Structure and envelope types and number of floor were collected from green building articles and school websites.

4.5 Selection Framework

The developed selection framework database is composed of two types of data, the LCC components data collected, computed, and analysed utilizing various methods, and the evaluation data collected from school boards. The data from school boards includes the evaluation of the measured LCC components and the weighting of criteria selections. The LCC data is evaluated using the Multi Attributes Utility Theory (MAUT), while the weighting of criteria is done using Analytic Hierarchy Process (AHP). Evaluation of LCC components and the weighting of criteria are performed based on experts' and decision makers' judgments via the evaluation of a specially-designed questionnaire.

4.5.1 Questionnaire (Survey)

The survey is designed to assist school boards in the selection of structure and envelope types for new school buildings based on an evaluation of their criteria and preferences. Hundreds of questionnaires were distributed to experts and decision makers in facility management and material & resources departments in school boards in Canada. These surveys, in both French and English, were distributed using different formats including paper copies, electronic files sent via emails, and web-based surveys. The survey consists of two main parts:

4.5.1.1 Weighting of Selection Criteria using (AHP)

Experts are asked to weight the selection criteria using the pairwise comparison method according to their importance. The evaluated criteria include initial costs, running costs, environmental impact costs, salvage value, and sustainability. The experts are asked primarily to compare the criteria in a column to criteria in a row by applying a qualitative scale that ranges between one and nine, as shown in Table 4.14.

Table 4.14 Pairwise comparison matrix for the selection criteria

Please perform a pair-wise comparison of importance using the following 1 to 9 scale:

1	2	3	4	5	6	7	8	9
Equally Preferred	←		*Stongly Preferred*		→		*Extremely Preferred*	

Example

	B	C
A	9	1

A is Extremely Preferred to B **A is Equally Preferred to C**

	Initial Costs (IC)	Running Costs (RC)	Environmental Impact Cost (EIC)	Salvage Value (SV)	Sustainability (S)
Initial Costs (IC)	1				
Running Costs (RC)		1			
Environmental Impact Costs (EIC)			1		
Salvage Value (SV)				1	
Sustainability (S)					1

4.5.1.2 Evaluation of the Measured LCC Components using the MAUT

The second part of the questionnaire is the evaluation of the measured components of the LCC utilizing the multi-attributes utility theory. Experts are given the minimum and maximum measured points and then asked to rank theses values according to their preference. The most-preferred values receive a score of 1.0 while the least-preferred value receives a score of 0.0. A utility curve developed for selection criteria based on the evaluation of the experts and decision makers consulted, is shown in Figure 4.2.

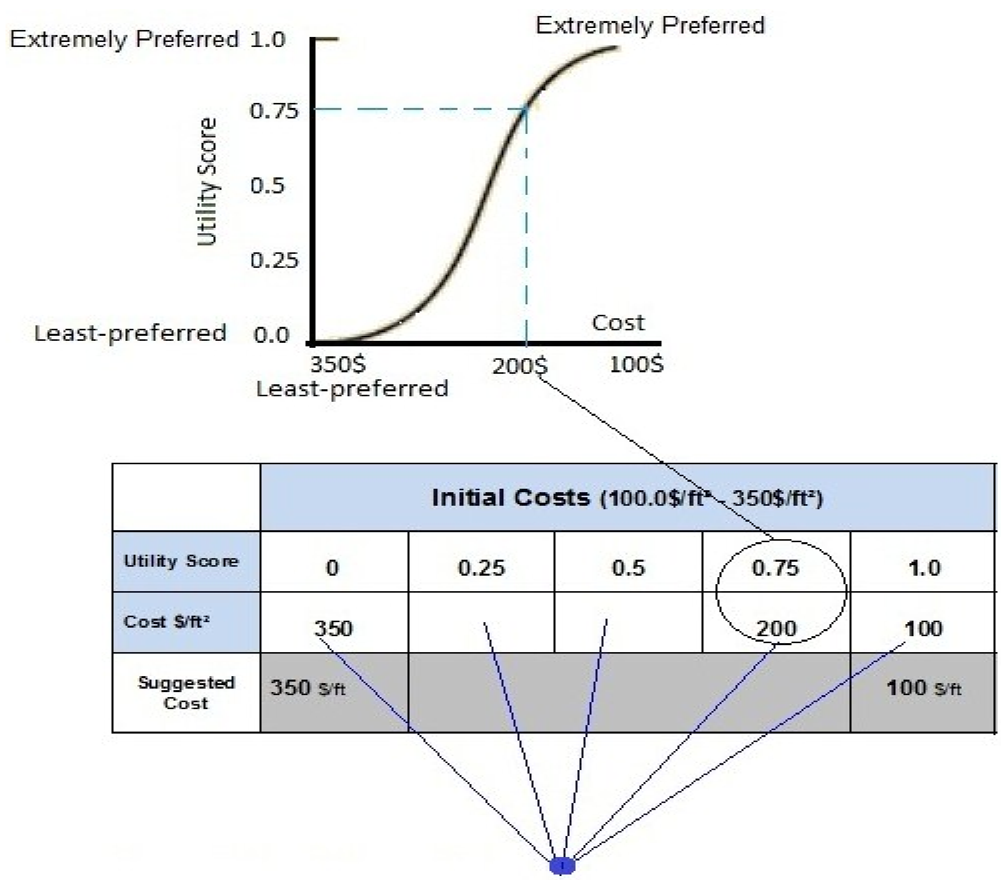


Figure 4.2 Utility curve development using experts' judgment

CHAPTER 5: SUSTAINABILITY ASSESSMENT MODEL DEVELOPMENT (SAM)

5.1 Introduction

This chapter includes the data analysis and the development process of the Sustainability Assessment Model. It also contains the results and the validation of the developed model.

5.2 Developed Assessment Model

The Sustainability Assessment Model is a part of the Selection Framework, which also contains LCC Forecasting Models, and is developed to enable school boards in Canada to select the structure and envelope type of their new school buildings. Life Cycle Assessment (LCA) is incorporated with Leadership in Energy and Environmental Design (LEED) ratings and assigned relevant scores to achieve a high level of sustainability assessment. The developed Assessment Model results in the selection of the system that achieves the highest sustainability scores from among the alternative. The model consists of three main components: an input module that defines the alternatives, a process module, which includes techniques for assigning scores, and an output model (which contains the assessed sustainability scores and selection), as shown in Figure 5.1. Three structure types are investigated in this study: concrete, steel, and wood, that could be used with four envelope systems: precast panels, steel stud, wood stud, and cavity wall, which results in seven tested alternatives. These alternatives include: steel stud wall, wood stud wall, steel stud with exterior brick, wood stud with exterior brick, steel with exterior wood, pre-cast concrete panels, masonry wall (face brick with concrete block back-up). Four types of roof are applied in this study: a solid concrete roof, precast hollow core slab, metal deck on steel joists, and wood roof on wood truss.

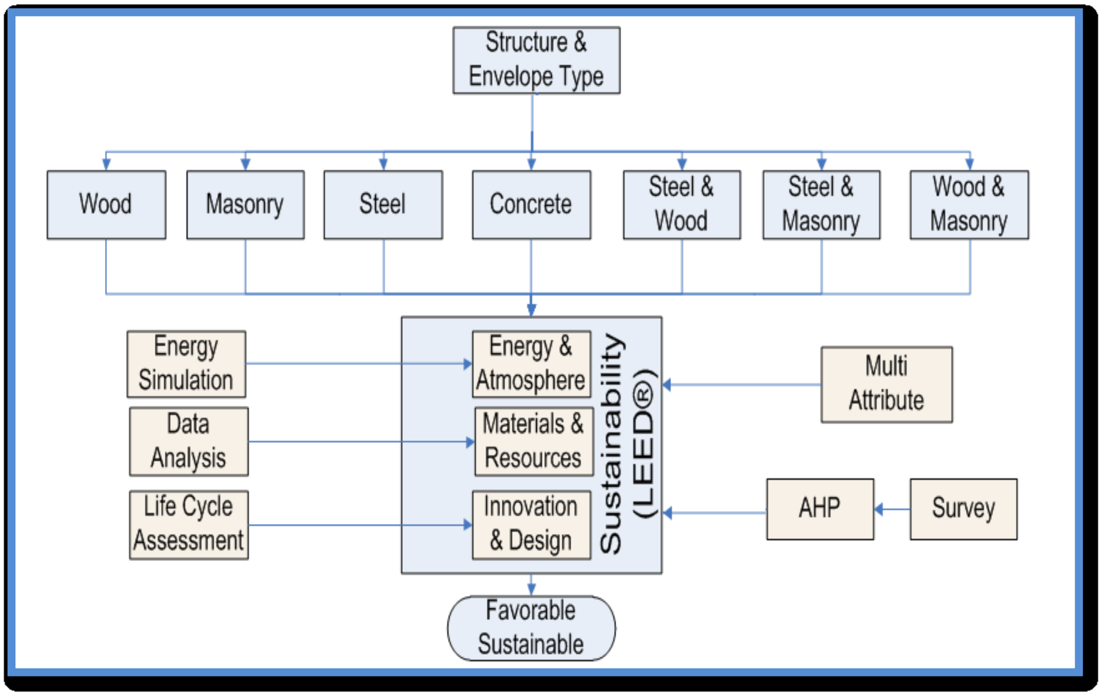
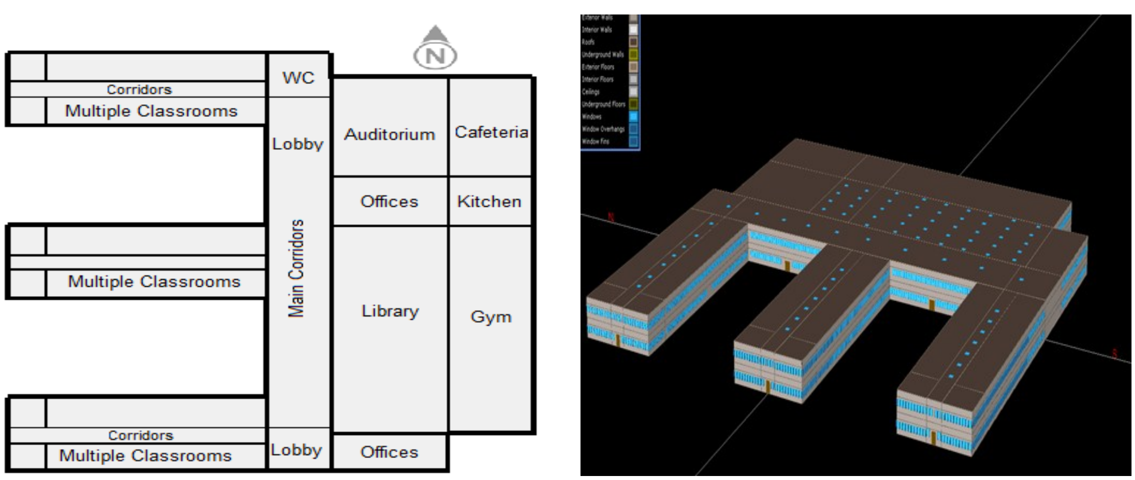


Figure 5.1 Sustainability Assessment Model Flowchart

Selection of the sustainable structure and envelope type for school buildings is done through the evaluation of three categories of the LEED rating system, namely, energy and atmosphere (energy consumption), material and resources (recyclability and reuse of material), and innovation and design process (life cycle assessment). Each LEED category is assigned a certain score and tested using different methods, techniques, and tools, as indicated in figure 5.1. For example, energy simulation is performed to measure the energy consumption, data analysis is applied on a large sample of sustainable school buildings to test the material and resources category, and environmental impact is measured using the LCA method.

5.2.1 Energy and Atmosphere Category

This test is done using energy consumption simulation, which is the official document required by the US green building council (USGBC 2010) to provide the estimated energy consumption of a designed building. A prototype model of a 250,000 ft^2 high school building in Montreal is tested using energy simulation software (eQUEST® version 3.64, 2010). Figure 5.2 shows the floor plan and the 3D rendering of the tested prototype model. The design of the fenestration, lighting systems (including electrical lights and daytime lighting), HVAC (heating, ventilation, and air conditioning) systems, building automation and controls, outside air treatment, and service water heating are defined based on the recommendations of ASHRAE 90.1 in the Advanced Energy Design Guide for K-12 school buildings, as shown in table 5.1. (ANSI/IESNA/ASHRAE 2008).



(a) (b)

Figure 5.2 (a) Prototype model floor plan with zones, (b) 3D model Rendering

Table 5.1 Prototype model description applying K-12 AEDG recommendations

Items	Prototype Characteristics
School type	Secondary school
Total gross area	250,000 ft^2
Number of floor	2 floors
Floor height	13.1 ft
Number of students	1500 student
Plan shape	E - shape
Building orientation	Long axis oriented (north-south)
Location (city)	Montreal, Canada
Climate zone	6a (cold- dry)
Occupancy	Fully occupied during school hours, partially year round
Peak plug loads	1.0 w/ft^2 for middle and high
Window Area	33% fenestration to gross wall area
Thermal transmittance of windows	U – (0.42)
Solar heat gain coefficient	(SHGC)-0.40
Percent conditioned	Fully heated and cooled

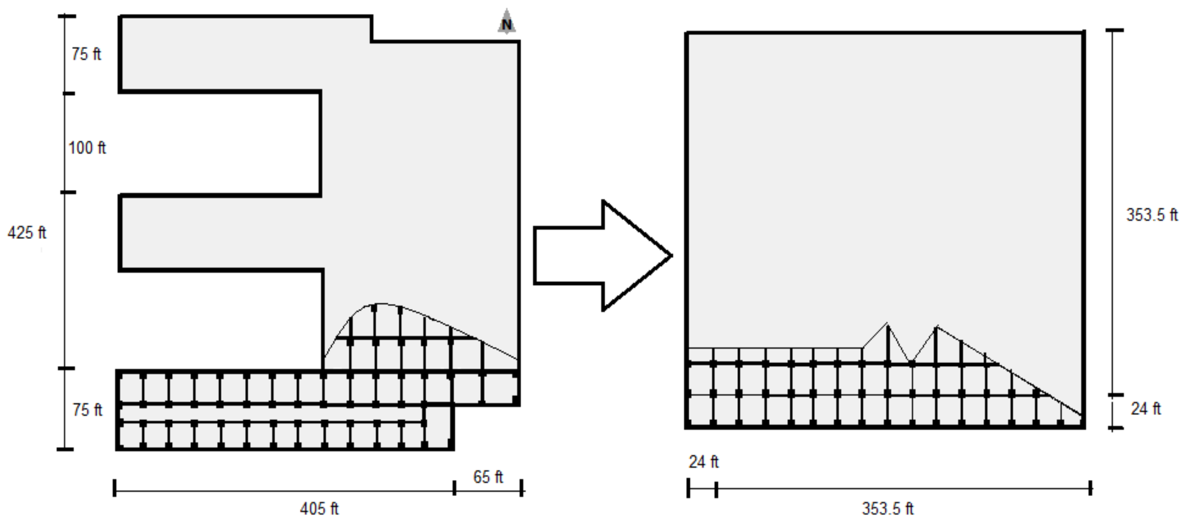
Three different test scenarios are applied into each type of exposure to test the performance of the various material and envelopes: no insulation at all, minimum code requirement for the climate zone (6a), and the ASHRAE advanced energy design guide recommendations for K-12 school buildings. The energy performance of the various envelope systems is measured for various scenarios by performing hourly energy simulations to calculate the monthly electricity and natural gas consumption. The energy simulation is done utilizing the eQUEST software developed by the United States Department of Energy (DOE). This simulation is performed based on identifying some energy input normalized and variable parameters that affect the energy consumption of school buildings and the overall energy costs. The normalized energy parameters include the building form and floor plate, building orientation, a building's internal loads and operating schedules. Since this study is done to measure the performance of the various facade and roof systems, these alternatives are defined in detail according to the applied scenario; no insulation, minimum allowable insulation, and the highly recommended insulation by ASHRAE, as shown in table 5.2. The energy category is assigned 1 to 19 LEED points, which range between an estimated 12% to 48% reduction of energy consumption compared to the ASHRAE 90.1 baseline. This test results in the assessment of a sustainability score in the energy and atmosphere category, and leads to the selection of the most suitable envelope type that has a higher reduction in energy consumption and obtains the highest LEED scores, as shown in figure 5.3.

Table 5.2 Wall and roof system specifications for different applied scenarios

	Item	No Insulation			Minimum Requirment			ASHRAE Recommendation		
No.	**Wall Type**	Thickness	Insu.	U- value	Thickness	Insu.	U- value	Thickness	Insu.	U- value
1	Pre cast wall	200 mm	N/A	U(0.25)	257mm	R-7	U(0.073)	290mm	R-13	U(0.026)
2	Masonry (Cavity Wall)	250mm	N/A	U(0.37)	307mm	R-7	U(0.098)	330mm	R-13	U(0.055)
3	Steel Stud	107mm	N/A	U(0.92)	107mm	R-7	U(0.142)	157mm	R-13+R7.5	U(0.050)
4	Wood Sud	107mm	N/A	U(0.74)	107mm	R-7	U(0.120)	157mm	R-13+R7.5	U(0.043)
5	Steel + Masonry brick	150mm	N/A	U(0.61)	157mm	R-7	U(0.115)	207mm	R-13+R7.5	U(0.046)
6	Wood+ Masonry brick	150mm	N/A	U(0.51)	157mm	R-7	U(0.109)	207mm	R-13+R7.5	U(0.045)
7	Steel + Wood Sud	107mm	N/A	U(0.74)	107mm	R-7	U(0.120)	157mm	R-13+R7.5	U(0.043)
No.	**Roof Type**	Thickness	Insu.	U- value	Thickness	Insu.	U- value	Thickness	Insu.	U- value
1	Solid concrete slab	150 mm	N/A	U(0.35)	240mm	R-13	U(0.055)	330mm	R-25	U(0.026)
2	Hollow core slab	150mm	N/A	U(0.30)	240mm	R-13	U(0.050)	330mm	R-25	U(0.020)
3	wood roof-wood truss	75 mm	N/A	U(0.57)	150mm	R-13	U(0.069)	250mm	R-13+R19	U(0.031)
4	Built up - Metal Deck	75mm	N/A	U(0.50)	150mm	R-13	U(0.076)	250mm	R-13+R19	U(0.035)

5.2.2 Life Cycle Assessment Category

Life cycle assessment components such as global warming potential, embodied energy usage, pollutants to water, land emissions, pollutants to air, and natural resource use are measured in this study and assigned five LEED points. The developed prototype model for the energy simulation is used in this test as well to assess the environmental impact associated with the different structures and exposure systems. ATHENA 2011 is the impact estimator software used to perform this test based on the LCA method (Athena Institute, Canada). This tool incorporates databases, which cover many of the building exposure systems and structure types. This software requires the description of the architecture, structural components, and the annual energy consumption that was calculated by the energy simulation software. Many input parameters and assemblies are defined into the software, such as footings, slabs on grade, columns and beams, floors, roofs, interior walls, exterior walls, windows, other material such as insulation, fire proofing and water proofing membranes. Since environmental impacts are assessed based on the type and bill of materials as indicated in Table 5.3, ATHENA software is developed for projects that have plain configuration (square & rectangular plans). The original plan is adjusted to account for some structural elements such as the number and the size of structural and architectural elements, as shown in Figure 5.3. Parameters such as the floor area, roof area, number of columns and number of beams, bay and span sizes, and column and beams dimensions are defined according to the adjusted structural framing plan. Seven various structure and exposure systems are investigated during 75 years of operation over the complete life cycle stages: manufacturing, transportation, construction, maintenance, operating, and end-of-life, as shown in Figure 5.4. The alternatives are assigned LEED scores according to their level of reduction of the environmental impact in each LCA component, such as global warming, energy, air, water, and land emissions.



(a) Original plan configuration (b) Adjusted plan configuration

Figure 5.3 Structural framing plan configurations used in life cycle assessment

Table 5.3 Bill of materials report for conventional steel school buildings

Material	Quantity	Unit
3 mil Polyethylene	127500	sf
5/8" Fire-Rated Type X Gypsum Board	275000	sf
Aluminum	0.34	Tons
Batt. Fiberglass	525000	sf(1")
Batt. Rockwool	50115	sf(1")
Concrete 20 MPa (flyash av)	1805	yd^3
Concrete 30 MPa (flyash av)	1589	yd^3
Foam Polyisocyanurate	1050000	sf(1")
Galvanized Decking	126.7	Tons
Galvanized Studs	347.8	Tons
Glazing Panel	0.6708	Tons
Low E Tin Glazing	22885	sf
Nails	0.025	Tons
Open Web Joists	115.6	Tons
Rebar, Rod, Light Sections	14.02	Tons
Roofing Asphalt	2363.6	lbs
Screws Nuts & Bolts	39.24	Tons

5.2.3 Material and Resources Category

The material and resources category is significantly affected by structure and envelope types. This category requires applying a prerequisite point rating, storage and collection of recyclables. The material and resources category is assigned 13 LEED scores and contains the reuse of major structural components, recyclability of content, the diversion of the disposal of construction waste, the use of regional materials and of rapidly renewable material, as shown in Table 5.4. A sample of 109 LEED-certified school buildings in the United Stated and Canada is analyzed in this study to determine the average obtained LEED® scores that can be achieved in this category by applying each structure and envelope type. Each certified building is studied separately and classified according to its structure and exposure systems. After classifying each school, each LEED credit is investigated to compute the total obtained scores. The total of the overall LEED scores is reached by adding up the scores obtained in each category of the sustainability assessment model, indicated in Figure 5.4.

Table 5.4 LEED®'s checklist of materials and resources category

				Materials & Resources	**13 Points**
Y			Prereq 1	**Storage & Collection of Recyclables**	Required
			Credit 1.1	**Building Reuse**, Maintain 75% of Existing Walls, Floors and Roof	1
			Credit 1.2	**Building Reuse**, Maintain 95% of Existing Walls, Floors and Roof	1
			Credit 1.3	**Building Reuse**, Maintain 95% shell and 50% non-shell	1
			Credit 2.1	**Construction Waste Management**, Divert 50%	1
			Credit 2.2	**Construction Waste Management**, Divert 75%	1
			Credit 3.1	**Resource Reuse**, Specify 5%	1
			Credit 3.2	**Resource Reuse**, Specify 10%	1
			Credit 4.1	**Recycled Content**, Specify 5% (post-consumer + ½ post-industrial)	1
			Credit 4.2	**Recycled Content**, Specify 10% (post-consumer + ½ post-industrial)	1
			Credit 5.1	**Local/Regional Materials**, 20% Manufactured Regionally	1
			Credit 5.2	**Local/Regional Materials**, of 20% Above, 50% Extracted Regionally	1
			Credit 6	**Rapidly Renewable Materials**	1
			Credit 7	**Certified Wood**	1

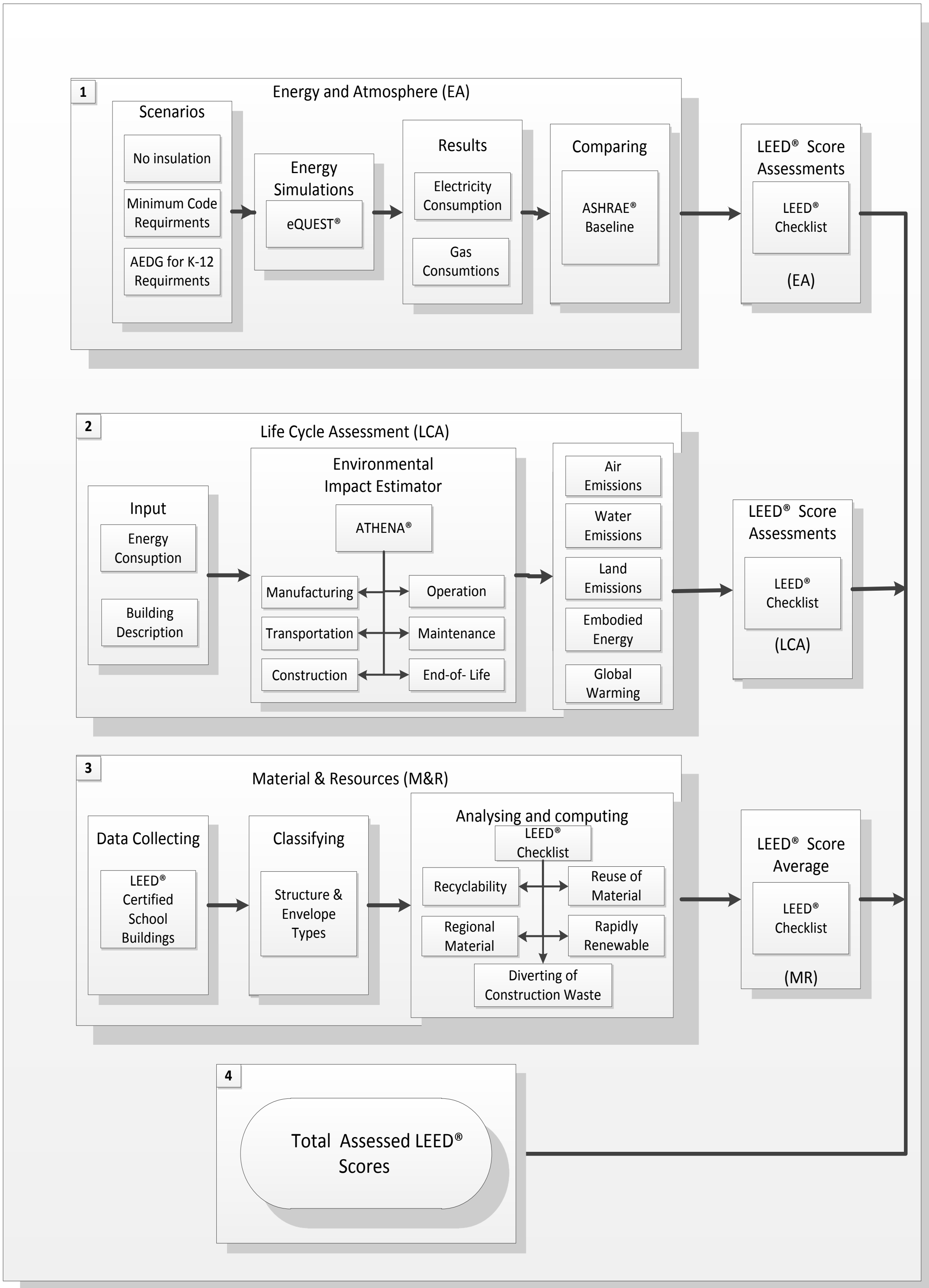


Figure 5.4 Flowchart of the developed Sustainability Assessment Model

5.3 Results of the Developed Sustainability Assessment Model

LCA is incorporated with the LEED scoring system in this model and assigned corresponding LEED scores to achieve a high level of sustainability assessment. The selection of the structure and exposure systems for school buildings (from a specific group of alternatives) is done through the evaluation of three categories of the LEED rating system; energy & atmosphere, materials & resources, and life cycle assessment. In this study, three structure types are investigated: concrete, steel, and wood, which are incorporated with four envelope systems: precast panels, steel stud, wood stud, and cavity wall. The following sub-sections present the results of the various tests performed with the developed sustainability assessment model.

5.3.1 Energy Simulation Results

The energy simulation is performed on a prototype model for two floors high school in Montreal using eQUEST 3.64. The results show that the peak electricity consumption occurs in June due to high temperatures that cause high energy consumption due to space cooling, equipment, and lighting. Even though July and August record the highest temperatures of the year, they correspond to the lowest energy consumption because of the school vacation. During winter -- January, February, December and March have the highest gas consumption due to the extreme cold weather that causes high energy consumption for space and water heating, as shown in Figure 5.5. Moderate energy consumption is recorded in April, May, September, and October due to the more moderate weather.

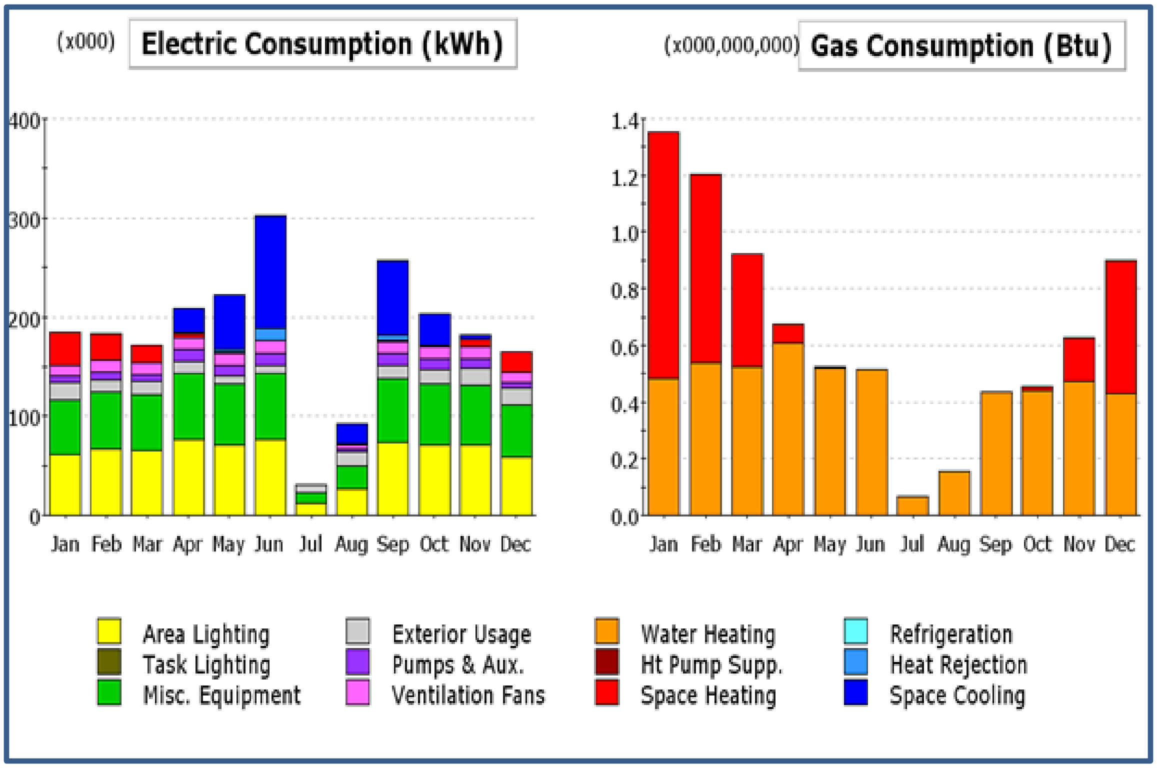


Figure 5.5 Annual Energy Consumption for one Tested scenario of High School

Three different energy simulation scenarios are performed to test different exposure possibilities: (a) no insulation at all, which reflects on the material's performance; (b) insulation at minimum code requirements, which represents the majority of buildings; and (c) insulation based on the K-12 AEDG recommendations to reduce the energy consumption of K-12 school buildings by 30%. Each scenario is applied on each envelope, normalizing the other energy input parameters and complying with the K-12 AEDG recommendations developed by ANSI/IESNA/ASHRAE based on ASHRAE 90.1. According to the ASHRAE 90.1standard, the average annual baseline energy consumption for high school buildings in climate zone 6 is approximately 88.0 kBtu/ft², which is equal to 25.8 KWh/ft². The minimum acceptable energy reduction to be certified by LEED is 12% compared to the ASHRAE baseline, which will grant the project one LEED point. Each two percentages of energy reduction beyond that12% will grant an additional 1 LEED point, up to 19 LEED points for a 48% reduction from the baseline. The results of the three studied scenarios are presented next.

5.3.1.1 No Insulation

This scenario was applied to test the performance of the envelope's material based only on their properties and resistance, without insulation. The results of this test show that the concrete envelope is the best alternative, with annual energy consumption of 20.07kWh/ft², which improves energy consumption by 22.17% over the baseline. Masonry, at 20.39kWh/ft², reduces energy consumption by 20.91%; wood with brick (21.28kWh/ft²) reduces consumption by 17.46%; steel with brick (21.48kWh/ft²) by 16.72%; wood and steel with wood (21.64kWh/ft²) reduces consumption by 16.07%; and steel (22.03kWh/ft²) reduces consumption by 14.59% over the baseline. Six LEED scores can be achieved by applying the concrete envelope while the steel envelope will achieve only 2 LEED scores, as shown in figure 5.6 and table 5.5.

Table 5.5 Annual energy consumption & LEED score (Case of "No Insulation")

Structure & Envelope Type	Steel	Wood	Concrete	Masonry	Steel+Masonry	Wood+Masonry	Steel+Wood
LEED'S Score (Points)	2	3	6	5	3	3	3
Energy Consumption (KWh/ft²)	22.03	21.64	20.07	20.39	21.48	21.28	21.64
Energy Reduction (Percentage %)	14.59%	16.07%	22.17%	20.91%	16.72%	17.46%	16.07%

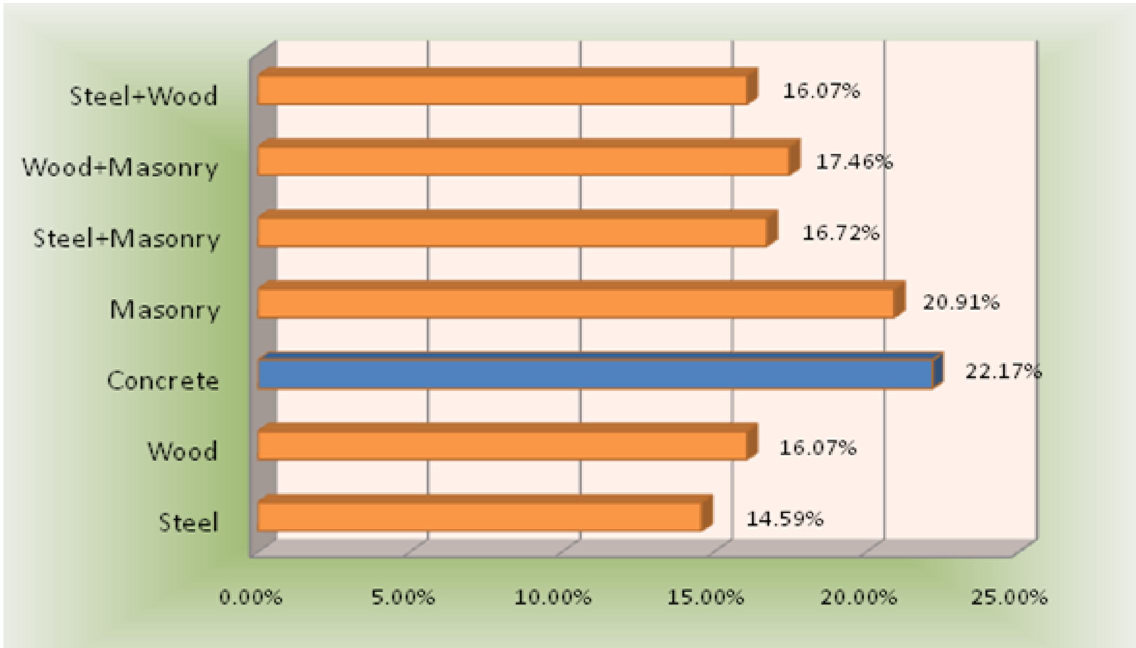


Figure 5.6 Annual energy consumption reduction over the ASHRAE's baseline (Case of "No insulation")

5.3.1.2 Achieving Minimum Code Requirements

This scenario is applied to test the performance of the envelope's material depending on their properties and the least allowable insulation. The results show that the concrete envelope records the highest energy saving, with annual energy consumption of 17.89kWh/ft². It minimizes energy consumption by 30.6% over the baseline. Masonry at 17.99kWh/ft² reduces consumption by 30.2%; wood with brick at 18.29kWh/ft² reduces by 29%; wood and steel plus wood at 18.33kWh/ft² reduces by 28.9%; steel with brick at 18.35kWh/ft² reduces by 28.91%; and steel at 18.43kWh/ft² reduces consumption by 28.5% over the baseline. Ten LEED points can be achieved by applying both concrete and masonry envelopes, while the other envelopes can achieve 9 LEED points, as shown in table 5.6.

Table 5.6 Annual energy consumption & LEED score (Case of minimum code requirements)

Structure & Envelope Type	Steel	Wood	Concrete	Masonry	Steel+Masonry	Wood+Masonry	Steel+Wood
LEED'S Score (Points)	9	9	10	10	9	9	9
Energy Consumption (KWh/ft²)	18.43	18.33	17.89	17.99	18.35	18.29	18.33
Energy Reduction (Percentage %)	28.55%	28.91%	30.62%	30.24%	28.90%	29.04%	28.91%

5.3.1.3 Achieving the Recommendations of AEDG for (K-12)

This scenario is applied to test the performance of the envelope's material based on their properties in combination with the insulation recommended by the ANSI/IESNA/ASHRAE 90.1-1999 standard for the different exposures in climate zone 6. The results of this simulation show that envelopes with the recommended insulation can perform with a similar energy performance and minimize energy consumption between (32.25% -32.54%), as shown in table 5.7. Applying the K-12 AEDG recommendations on conventional school buildings in Montreal showed that it was possible to achieve 11 LEED scores and reduce the energy consumption by 32.5%.

Table 5.7 Annual energy consumption & LEED (Case of "K-12 AEDG requirements")

Structure & Envelope Type	Steel	Wood	Concrete	Masonry	Steel+Masonry	Wood+Masonry	Steel+Wood
LEED'S Score (Points)	11	11	11	11	11	11	11
Energy Consumption (KWh/ft²)	17.41	17.39	17.43	17.47	17.42	17.41	17.39
Energy Reduction (Percentage %)	32.48%	32.54%	32.40%	32.25%	32.46%	32.48%	32.54%

5.3.2 Life Cycle Assessment Results

Life cycle assessment is incorporated into the LEED scoring system and assigned LEED scores to develop a sustainability assessment model to measure the impact of conventional high school buildings throughout 75 years of operation. The results of the LCA of each structure and envelope type in each life cycle stage are presented in the following sub-sections.

5.3.2.1 Energy Consumption during the Manufacturing Stage

From the LCA model, wood buildings and wood buildings with exterior brick are found to have the lowest energy consumption during the manufacturing stage, while steel buildings and steel buildings with brick represent the highest energy consumption compared to the other systems. Wood and wood with brick buildings consume 5.46 million kWh, steel with wood 8.15 million kWh, concrete 9.42 million kWh, masonry 10.8 million kWh, and steel and steel with brick 11.59 million kWh during the manufacturing stage, as shown in Table 5.8.

5.3.2.2 Energy Consumption during the Construction Stage

The model results indicate that steel buildings and steel buildings with exterior brick have the lowest energy consumption during the construction, while masonry and concrete buildings represent the highest energy consumption compared to the other systems. Steel and steel with brick buildings consume 0.3 and 0.32 million kWh respectively, steel with wood 0.35 million kWh, wood and wood with brick 0.36 and 0.39 million kWh, respectively, concrete 0.6 million kWh, and masonry 1.0 million kWh during the construction stage, as shown in Table 5.8.

5.3.2.3 Energy Consumption during the Maintenance Stage

Steel buildings and wood buildings have the lowest energy consumption during the maintenance stage, while masonry and concrete buildings represent the highest energy consumption compared to the other systems. Steel and wood with or without exterior brick consume 0.11 million kWh, concrete 0.14 million kWh, and masonry 0.34 million kWh during the maintenance stage, as shown in Table 5.8.

5.3.2.4 Energy Consumption at the End of Life Stage

The model shows that steel buildings and steel buildings with exterior brick have the lowest energy consumption at the end of life stage, while masonry and concrete buildings represent the highest energy consumption. Steel and steel with brick buildings consume 0.33 and 0.34 million kWh, respectively, steel with wood 0.35 million kWh, wood and wood with brick 0.37 and 0.38 million kWh, respectively, concrete 0.59 million kWh, and masonry 1.6 million kWh at the end-of-life stage, as shown in Table 5.8.

5.3.2.5 Total Energy Consumption

The total operating energy consumption discussed in the four-mentioned tests was added to the other stages' consumption in order to estimate the total energy consumption in Table 5.8. The total energy consumption shows that masonry buildings and concrete buildings have the lowest total energy consumption over their entire life cycle span. Masonry buildings consume about 484 million kWh, concrete 494 million kWh, wood and brick buildings consume 495 million kWh, wood buildings 502 million kWh, steel and wood and steel and brick 505 million kWh, and steel 516 million kWh over lifespans of 75 years. Masonry buildings have the lowest overall energy consumption, and will earn 1 additional LEED score.

Table 5.8 Primary energy consumption overall life cycle stages

Life Stages	Manufacture	Construction	Maintenance	End-Of-Life	Operating	Total Effects
Alternative	Total (KWh)	Total(KWh)	Total (KWh)	Total (KWh)	Total(KWh)	
Concrete	9425138	608571	136998	594200	242852737	253617644
Steel	11480751	305867	112356	337838	280100896	292337708
Wood	5523111	364052	112356	378374	273025150	279403043
Masonry	10842283	998335	136999	1602231	249172361	262752209
Steel+Masonry	11590170	328731	112356	347279	269859998	282238534
Wood+Masonry	5461748	390193	336777	386664	266207035	272782417
Steel+Wood	8150155	355862	112356	356526	273025150	282000049

5.3.2.6 Global Warming Potential (GWP)

GWP is expressed on an equivalency basis relative to CO_2 emissions in kg. The highest global warming emission is generated during the operating stage (90% of the overall effects) following by the manufacturing stage. Demolishing a building is recorded as generating GWP emissions that are twice as high as those of the construction stage, as shown in Table 5.9.

Table 5.9 Global warming potential overall life cycle stages

Life Stages / Alternative	Manufacturing	Construction	Maintenance	End - Of - Life	Operating Energy	Total Effects
Concrete	3518008	52058	122521	71118	47238103	51001808
Steel	2765806	32113	93580	63656	54670890	57626047
Wood	1430666	30053	93580	78129	53260744	54893175
Masonry	4031140	116889	122521	295573	48500338	53066461
Steel+Masonry	2807897	32272	93580	63721	52629177	55626650
Wood+masonry	1464713	30424	180707	77866	51900373	53654084
Steel+Wood	1824862	30010	93580	72696	53260744	55281895

Concrete buildings produce the lowest overall global warming potential impact, while steel buildings contribute the highest, compared to the other systems studied. Concrete buildings produce about 51 million (kg CO_2 eq.), masonry 53 million (kg CO_2 eq.), wood with brick buildings produce 53.5 million (kg CO_2 eq.), wood and steel and wood buildings 55 million (kg CO_2 eq.), steel and brick 55.5 million (kg CO_2 eq.), and steel 57.5 million (kg CO_2 eq.) over a 75-year lifespan, as can be seen in figure 5.7. Concrete buildings have the lowest overall global warming impact and will thus achieve 1 additional LEED score.

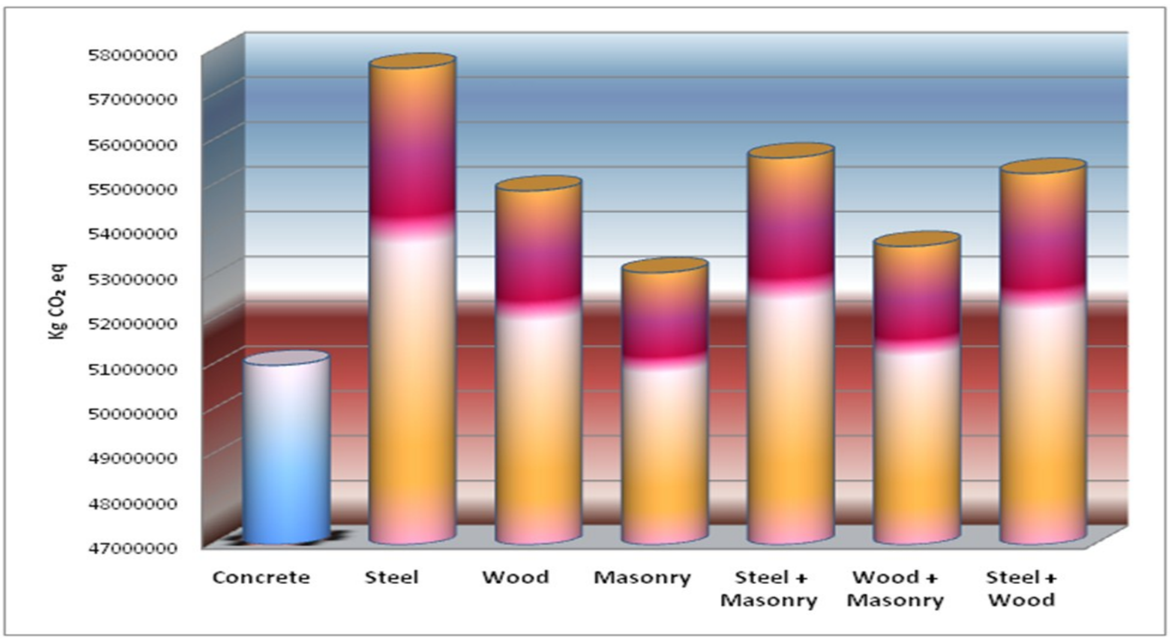


Figure 5.7 Comparison of total global warming potential over all life cycle stages

5.3.2.7 Air Emissions

Concrete buildings contribute the least to overall air emissions while steel buildings contribute the highest air. Concrete and masonry buildings produce 772 and 798 million (indexed) air emissions, respectively, while wood and steel buildings contribute 828 and 860 million (indexed) respectively, as presented in table 5.10. Concrete buildings can achieve 1 LEED score in this factor.

5.3.2.8 Land Emissions

Buildings made of wood contribute the lowest overall land emissions, while masonry buildings contribute the highest land, as shown in table 5.10. Wood with brick and wood buildings produce 0.97 million (indexed) land emissions, while masonry buildings contribute 1.8 million (indexed). Wood and wood and brick buildings can achieve 1 LEED point for the land emission factor.

5.3.2.9 Water Emissions

Concrete buildings contribute the lowest overall water emissions and steel buildings contribute the highest. Concrete and masonry buildings produce 7.08×10^{12} and 7.31×10^{12} (indexed) water emissions, respectively, while wood and steel buildings contribute 7.90×10^{12} and 8.20×10^{12} (indexed) respectively, as can be seen in table 5.10. Concrete buildings can achieve 1 LEED score in the water emissions factor.

Table 5.10 Total environmental impacts for each structure and exposure type

Structure & Envelope Type	Concrete	Steel	Wood	Masonry	Steel Masonry	Wood Masonry	Steel Wood
Air Emission (Index)	7.73E+08	8.61E+08	8.28E+08	7.98E+08	8.31E+08	8.11E+08	8.32E+08
Energy (KWh)	4.94E+08	5.16E+08	5.02E+08	4.84E+08	5.05E+08	4.95E+08	5.05E+08
Land Emission (Index)	1.20E+06	1.09E+06	9.72E+05	1.84E+06	1.07E+06	9.70E+05	1.02E+06
Resource (Tons)	61209	71325	33857	65091.5	70758	33643	36965
Water Emission (Index)	7.08E+12	8.20E+12	7.90E+12	7.31E+12	7.90E+12	7.71E+12	7.93E+12
Global Warming (kgco2)	5.10E+07	5.76E+07	5.49E+07	5.31E+07	5.56E+07	5.37E+07	5.53E+07

5.3.3 Material and Resources Results

Most LEED certified school buildings in the US and Canada are built of concrete with masonry walls, and built of steel structure with exterior brick. The tested sample (109 green schools) of certified schools is representative, since the total number of certified schools does not exceed 250. The highest score emissions in the materials and resources category is recorded in wood structures with exterior wood walls, (10 scores); while the lowest score is recorded in masonry buildings and in steel with masonry walls (2 scores). Table 5.11 presents the LEED scores earned by various alternatives.

Table 5.11 Sample of achieved LEED scores in materials & resources category

Alternatives	Concrete (CC)	Masonry (CM)	Steel (SS)	Wood (WW)	Steel (SC)	Wood (WC)	Steel (SW)
Achieved LEED® scores in materials and resources category	8	7	6	7	6	4	3
	6	6	6	4	6	6	8
	4	6	5	7	5	5	6
	4	4	4	10	2	8	6
	4	3	5	6	7	5	5
	5	2	3	6	6	5	5
	7	7	5	5	4	6	8
	6	5	5	5	5	5	6

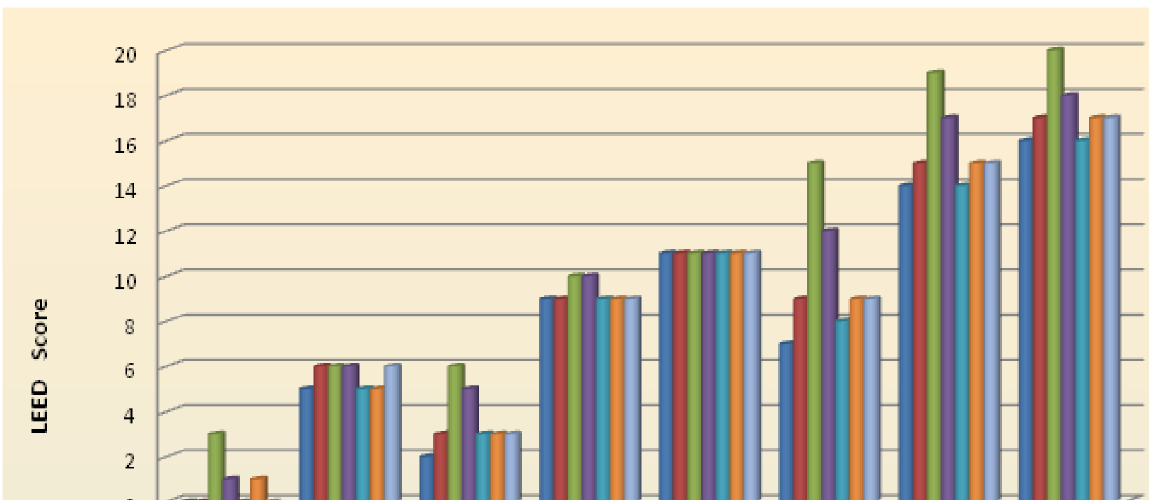
The results of materials and resources category analysis show that wood buildings recorded the highest LEED score average, while steel buildings had the lowest. Fourteen certified wooden school buildings recorded an average of 6.35 (LEED score), eight steel with wood exposure schools achieved an average of 5.87 (LEED score), twelve concrete schools recorded an average 5.83 score, 27 masonry schools recorded an average 5.7 score, 10 wood and brick schools recorded a 5.4 score, 24 steel with brick exposure schools recorded a 5.29 score, and fourteen steel schools recorded an average of 4.83 (LEED score), as presented in Figure 5.8.

	Steel	Wood	Concrete	Masonry	Steel+Masonry	Wood+Masonry	Steel+Wood
Number of Tested Schools	14	14	12	27	24	10	8
Average of LEED'S Score	4.85	6.35	5.83	5.7	5.29	5.4	5.87

Figure 5.8 Average of LEED scores and number of tested certified schools in the material and resources category

5.3.4. Overall Results

Concrete and masonry school buildings prove to have high energy consumption rates and contribute more global warming impacts during certain life cycle stages such as manufacturing, construction, and demolition. On the other hand, they prove to have lower annual energy consumption and lower environmental impact throughout the operating stage as well as throughout their overall life cycle span compared to other counterparts. The most favourable sustainable structure and envelope type is proven to be concrete, which could achieve the highest LEED scores, 15, 19, and 20 in different scenarios. The second favourable structure and exposure type is masonry, which could achieve scores of 12, 17, and 18. The lowest sustainability level is obtained by applying a steel structure and envelope, which only could obtain 7, 14, and 16 LEED scores, as shown in Figure 5.9.



	LEED Score in Life Cycle Assessment	LEED Score in Material &Resources	LEED Score in Energy "No Insulation"	LEED Score in Energy "Minmum Code"	LEED Score in Energy "ANSI/IESNA/ASHRAE"	Total LEED Score "No Insulation"	Total LEED Score "Minmum Code"	Total LEED Score "ANSI/IESNA/ASHRAE"
Steel	0	5	2	9	11	7	14	16
Wood	0	6	3	9	11	9	15	17
Concrete	3	6	6	10	11	15	19	20
Masonry	1	6	5	10	11	12	17	18
Steel+Masonry	0	5	3	9	11	8	14	16
Wood+Masonry	1	5	3	9	11	9	15	17
Steel+Wood	0	6	3	9	11	9	15	17

Figure 5.9 Overall result of the developed sustainability assessment model

5.4 Summary

- Incorporating life cycle assessment into LEED scoring in the sustainability assessment model is a significant means to measure the comprehensive sustainability performance for various structure and exposure types.
- The averages of the LEED scores in the material and resources category have not exceeded 6 points out of 13, which indicates the level of the obstacles and shortages in the construction industry in applying recyclability and the reuse of building materials.
- Applying the recommendations of the AEDG for K-12 schools resulted in a valuable energy saving, and equivalent energy performances for the various exposures, but it will increase the initial costs for steel and wooden buildings.
- Selecting an alternative based on its performance in only one life cycle stage, or neglecting a vital stage such as operations, will not lead to the best decision. Therefore, the complete life cycle stages should be considered in the selection process.
- Life cycle assessment should be included in the LEED scoring system as an independent category, and more points should be assigned accordingly.

CHAPTER 6: DEVELOPMENT OF THE LCC MODELS AND SELECTION FRAMEWORK

6.1 Introduction

This chapter presents the development of the Life Cycle Costing Forecasting Models and the Selection Framework for conventional and sustainable school buildings. Many techniques are utilized in the development as well as in the data analysis, such as linear regression, AHP, MAUT, LCA, energy simulation, LCC, sensitivity analysis, simulation, reliability analysis, risk analysis, and validation. The responses of the designed survey are analyzed in this chapter and the results of the selection criteria evaluation are discussed. The computing of LCC components such as initial costs, energy costs, major repairs costs, operating and maintenance costs, environmental impact costs, and salvage value are explained in detail in this chapter as follows.

6.2 Initial Costs (Conventional School Buildings)

6.2.1 Initial Costs' Parameters

The RS Means is used in this study to estimate the construction costs by identifying some significance parameters. Several input parameters are defined to calculate the initial costs, including school level, school area, floor height, number of floors, structure type, envelope type, city, and year of construction, as shown in Figure 6.1. The description possibilities of each parameter include;

- School level: Elementary, middle, and high school
- School area: 45000, 75000, 125000, 175000, and 250000ft^2

- Number of floors: 1, 2, 3, and 4 floors
- Floor height: 13.1 ft
- Structure type: Steel frame, wood frame, and concrete frame
- Envelope type: steel studs, wood studs, concrete brick, masonry wall, and precast concrete panels.
- City: Montreal, Canada
- Year of construction: 2011

6.2.2 Initial Costs (Breakdown of Construction Costs)

After identifying the parameters, the model is applied to estimate the construction costs for a new school building. The output of the RS Means is presented in a detailed table that has a breakdown of the component cost used to develop the base building cost.

The breakdown cost components include:

Substructure: foundations, slab on grade, basement excavation and walls.

Super structure (Shell): floor construction, roof construction, exterior walls, windows, doors, roof coverings and roof openings.

Services: elevators and lifts, plumbing fixtures, domestic water distribution, rain water drainage, energy supply, cooling systems, sprinklers, standpipes, electrical services/distribution, lighting and branch wiring, communications and security, and other electrical systems.

Interiors: partitions, interior doors, fittings, stair construction, wall finishes, floor finishes, ceiling finishes.

Equipment and furnishings: institutional equipment, HVAC, and other equipment.

Contractor fees: general conditions, overhead, contingency, and profits.

Architecture fee: design, drawing, and supervision.

After estimating the breakdown component costs, they are added to calculate the subtotal cost which is then added to the contractor's and architecture fees. The total building cost is then provided in a square foot cost as shown in Table 6.1.

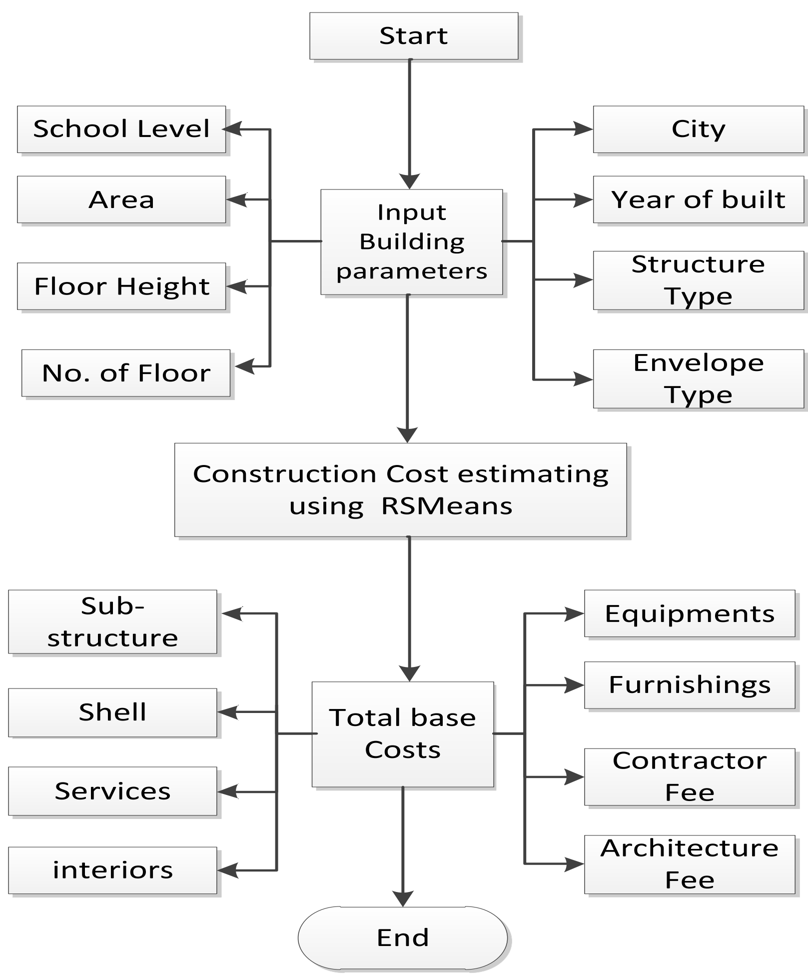


Figure 6.1 Initial cost estimating process using RS Means

Table 6.1 Detailed initial costs for substructure and shell (RS. Means 2011)

	Square Foot Cost Estimate Report
Estimate Name:	Untitled
Building Type:	School, High, 2-3 Story with Face Brick with Concrete Block Back-up / R/Conc. Frame
Location:	MONTREAL, PQ
Story Count:	2
Story Height (L.F.):	13
Floor Area (S.F.):	175000
Labor Type:	Union
Basement Included:	No
Data Release:	Year 2011
Cost Per Square Foot:	$152.40
Building Cost:	$26,668,500

Costs are derived from a building model with basic components.
Scope differences and market conditions can cause costs to vary significantly.

Item	Details	% of Total	Cost Per S.F.	Cost
A Substructure		4.70%	$5.30	$928,000
A1010	Standard Foundations		$1.28	$224,000
	3 KSF, 12" deep x 24" wide			
	6 KSF, 5' - 0" square x 16" deep			
	6 KSF, 6' - 0" square x 20" deep			
A1030	Slab on Grade		$3.09	$541,000
	Slab on grade, 4" thick, non industrial, reinforced			
A2010	Basement Excavation		$0.08	$14,500
	on site storage			
A2020	Basement Walls		$0.85	$148,500
	12" thick			
B Shell		32.10%	$36.55	$6,396,500
B1010	Floor Construction		$11.04	$1,932,000
	reinforcing, 500K load, 10'-14' story height, 375 lbs/LF, 4000PSI			
	superimposed load, 194 PSF total load			
B1020	Roof Construction		$7.76	$1,358,500
	load, 20" deep beam, 9" slab, 152 PSF total load			
B2010	Exterior Walls		$5.83	$1,020,500
	thick, perlite core fill			
B2020	Exterior Windows		$4.99	$872,500
	opening, 2 intermediate horizontals			
	Glazing panel, insulating, 1/2" thick, 2 lites 1/8" float glass, tinted			
B2030	Exterior Doors		$0.60	$105,000
	hardware, 6'-0" x 10'-0" opening			
	x 7'-0" opening			
	8'-0" opening			
B3010	Roof Coverings		$6.29	$1,100,000
	Roofing, single ply membrane, EPDM, 60 mils, fully adhered			
	.020" thick, 0.87 PSF			
	Insulation, rigid, roof deck, polyisocyanurate, 2#/CF, 2" thick			
	Insulation, rigid, roof deck, polyisocyanurate, tapered for drainage			
	reglet, .032" counter flashing			
	Roof edges, aluminum, duranodic, .050" thick, 6" face			
B3020	Roof Openings		$0.05	$8,000
	galvanized steel, 165 lbs			

Table 6.2 Detailed initial costs for school services (RS. Means 2011)

D Services		38.80%	$44.17	$7,729,500
D1010	**Elevators and Lifts**		$0.76	$133,500
	Hydraulic passenger elevator, 2500 lb., 2 floor, 125 FPM			
D2010	**Plumbing Fixtures**		$4.78	$837,000
	Water closet, vitreous china, bowl only with flush valve, floor mount			
	Urinal, vitreous china, wall hung			
	Lavatory w/trim, wall hung, PE on CI, 20" x 18"			
	Kitchen sink w/trim, countertop, stainless steel, 44" x 22" triple bowl			
	OD			
	Service sink w/trim, PE on CI, corner floor, 28" x 28", w/rim guard			
	Service sink w/trim, PE on CI,wall hung w/rim guard, 24" x 20"			
	Group wash fountain, stainless steel, circular, 54" diam			
	Shower, stall, baked enamel, terrazzo receptor, 36" square			
	Water cooler, electric, wall hung, wheelchair type, 7.5 GPH			
D2020	**Domestic Water Distribution**		$0.66	$115,000
	GPH			
D2040	**Rain Water Drainage**		$0.66	$115,000
	Roof drain, CI, soil,single hub, 4" diam, 10' high			
	Roof drain, CI, soil,single hub, 4" diam, for each additional foot add			
	Roof drain, CI, soil,single hub, 5" diam, 10' high			
	Roof drain, CI, soil,single hub, 5" diam, for each additional foot add			
D3010	**Energy Supply**		$4.61	$806,500
	water, 100,000 SF, 1mil CF, total 3 floors			
D3030	**Cooling Generating Systems**		$15.17	$2,654,500
	colleges, 60,000 SF, 230.00 ton			
D4010	**Sprinklers**		$2.40	$420,500
	Wet pipe sprinkler systems, steel, light hazard, 1 floor, 50,000 SF			
	50,000 SF			
D4020	**Standpipes**		$0.28	$49,000
	floor			
	additional floors			
D5010	**Electrical Service/Distribution**		$1.12	$196,500
	3 phase, 4 wire, 120/208 V, 2000 A			
	2000 A			
	2000 A			
D5020	**Lighting and Branch Wiring**		$9.19	$1,608,000
	with transformer			
	Wall switches, 2.0 per 1000 SF			
	Miscellaneous power, 1.2 watts			
	Central air conditioning power, 4 watts			
	Motor installation, three phase, 460 V, 15 HP motor size			
	460 V 15 HP, 575 V 20 HP			
	10 fixtures @32watt per 1000 SF			
D5030	**Communications and Security**		$3.87	$677,000
	and wire, sound systems, 100 outlets			
	detectors, includes outlets, boxes, conduit and wire			
	conduit			
	and wire, master clock systems, 50 rooms			
	and wire, master TV antenna systems,100 outlets			
	Internet wiring, 2 data/voice outlets per 1000 S.F.			
D5090	**Other Electrical Systems**		$0.67	$117,000
	diesel engine with fuel tank, 250 kW			

Table 6.3 Detailed initial costs for interiors, equipment, and total costs (RS Means 2011)

C Interiors		21.50%	$24.51	$4,290,000
C1010	**Partitions**		$4.95	$865,500
	finish			
	furring			
C1020	**Interior Doors**		$1.59	$277,500
	flush, 3'-0" x 7'-0" x 1-3/8"			
C1030	**Fittings**		$1.11	$195,000
	Toilet partitions, cubicles, ceiling hung, stainless steel			
	Chalkboards, liquid chalk type, aluminum frame & chalktrough			
C2010	**Stair Construction**		$0.61	$107,000
	landing			
C3010	**Wall Finishes**		$3.03	$529,500
	Painting, masonry or concrete, latex, brushwork, primer & 2 coats			
	filler			
	Wall coatings, acrylic glazed coatings, maximum			
	Ceramic tile, thin set, 4-1/4" x 4-1/4"			
C3020	**Floor Finishes**		$6.66	$1,166,000
	Carpet, tufted, nylon, roll goods, 12' wide, 36 oz			
	Carpet, padding, add to above, minimum			
	Terrazzo, maximum			
	Vinyl, composition tile, maximum			
C3030	**Ceiling Finishes**		$6.57	$1,149,500
	& channel grid, suspended support			
E Equipment & Furnishings		3.00%	$3.40	$595,000
E1020	**Institutional Equipment**		$2.29	$400,000
	proof, economy			
	stainless steel			
	Architectural equipment, laboratory equipment, cabinets, wall, open drawer units			
E1090	**Other Equipment**		$1.11	$195,000
	suspended type, electrically operated			
	manual operation, 15 tier, economy (per seat)			
	universal, economy			
F Special Construction		0.00%	$0.00	$0
G Building Sitework		0.00%	$0.00	$0
SubTotal		100%	$113.94	$19,939,000
Contractor Fees (General Conditions,Overhead,Profit)		25.00%	$28.49	$4,985,000
Architectural Fees		7.00%	$9.97	$1,744,500
User Fees		0.00%	$0.00	$0
Total Building Cost			$152.40	$26,668,500

6.2.3 Various Scenarios Tested for Initial Costs

Computing of the initial costs in this study is performed by applying different scenarios to build a correlation between the input parameters and the total square foot base cost. Each structure and envelope type is estimated for different school levels at specific area sizes and number of floors, resulting in 21 tested scenarios. Each area size is applied on a different number of floors resulting in 20 various tested scenarios as shown in Figure 6.2. Four hundred and twenty (420) construction cost estimating scenarios result from the combination of the complete range of input parameters for new school buildings in Montreal.

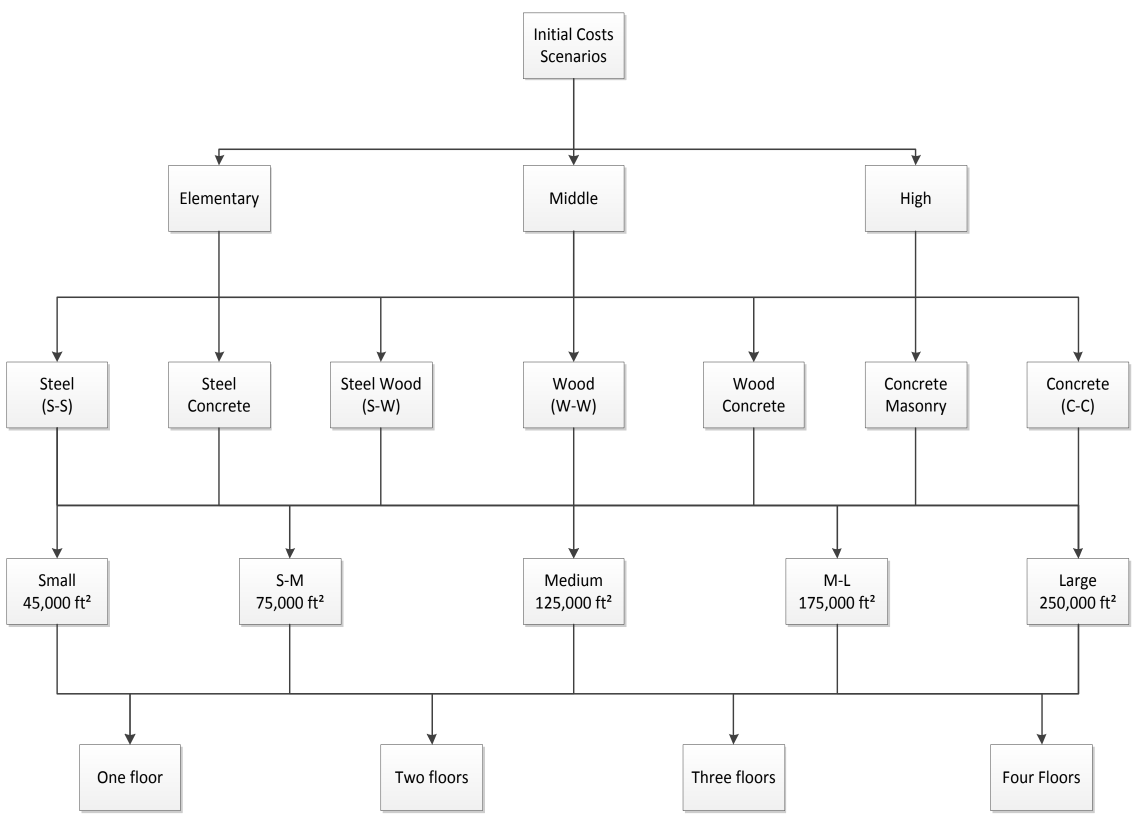


Figure 6.2 Various scenarios tested for initial costs

Seven cost scenarios are grouped together and evaluated according to the structure and envelope types of a new school building in order to select the most economically viable alternative. For example, to estimate the initial costs for a conventional elementary school building in Montreal in 2011 with a medium-sized area (125,000ft²) and two floors, a result is produced as indicated in Table 6.4. This Table shows that the wooden school structure and envelope has the lowest initial costs while the precast concrete school building has the highest costs, with moderate costs recorded for steel school buildings. The results of the initial costs estimation using the RS Means are summarized in 60 different cost tables to find the correlation between structure and envelope types and other input parameters with overall construction costs.

Table 6.4 Initial costs per square foot for various structure and envelope types

Cost Per Square Foot of Floor Area of School Buildings							
	School Level	Numbet of floor	Area	Floor Height	City	Year	
	Elementary	2	125,000 ft²	13.1 ft	Montreal	2011	
Structure & Envelope Type	**S-S**	**S-C**	**S-W**	**W-W**	**W-C**	**C-M**	**C-C**
Substructure	$9.76	$9.76	$9.76	$7.14	$7.14	$5.54	$5.54
Shell	$23.35	$23.35	$23.35	$10.82	$10.82	$31.71	$31.71
Exterior wall	$2.34	$5.74	$2.86	$2.86	$5.74	$6.89	$11.70
Interiors	$24.65	$24.65	$24.65	$24.65	$24.65	$24.65	$24.65
Services	$52.39	$52.39	$52.39	$52.39	$52.39	$52.39	$52.39
Equipments and Furnishing	$0.20	$0.20	$0.20	$0.20	$0.20	$0.20	$0.20
Sub total	$112.69	$116.09	$113.21	$98.06	$100.94	$121.38	$126.19
Contractor fee (25%)	$28.17	$29.02	$28.30	$24.52	$25.24	$30.35	$31.55
Architectural fee (7%)	$9.86	$10.16	$9.91	$8.58	$8.83	$10.62	$11.04
Total	**$150.7**	**$155.3**	**$151.4**	**$131.2**	**$135.0**	**$162.3**	**$168.8**

6.2.4 Data Preparation for Modeling

The input parameters (independent variables) for the initial costs are gathered from the RS Means. Some of these variables are normalized, such as the city, year of construction, and floor height. The other parameters, such as structure and exposure type, school level, number of floor, and school area are variables and have a significant effect on the initial costs. These factors are investigated in this research to develop their correlation to the resulted initial costs (dependent factor). The computed initial costs from RS Means include about 420 data points. Eighty percent of this data, (336 points) are used to build the initial cost prediction models for conventional school buildings. Twenty percent of the data (84 points) are randomly picked and excluded from the analysis to be used for model validation. The data is sorted based on structure and envelope type in order to be used in developing the prediction model, as shown in Table 6.5. This data sorting process resulted in seven data sets with 60 data points in each.

Table 6.5 Sample of data sorting and preparation for modeling

School Area (ft²)	No. of Floor	Type SS	School Level	Initial Costs ($/ft²)
175000	1	1	1	$151.54
250000	1	1	1	$150.08
45000	2	1	1	$160.01
250000	3	1	1	$147.27
45000	4	1	1	$170.54
75000	4	1	1	$163.31
250000	3	1	2	$140.96
75000	4	1	2	$157.80
125000	2	1	3	$144.97
45000	3	1	3	$163.70
175000	3	1	3	$143.75
250000	3	1	3	$140.22
45000	4	1	3	$169.42
125000	4	1	3	$149.59

6.2.4.1.1 Model Development Process

The main aim of the model development is to find correlations between the predictors and the response variables. The multiple linear regression technique was utilized to address the correlation and to develop prediction models for each structure and exposure type. Regression model development methodology consists of three major stages; preliminary diagnostics on data quality, the model development process, and model validation, as shown in Figure 6.3. The preliminary data checks include two steps: determining any possible relationship and interaction of data, and performing the best subset regression analysis. The next stage is the model development process which has four major steps: building the regression model, testing basic factors, performing residual analysis, and selecting the model for validation. The final stage in the model development process is performing the validation. Each step in the various development process stages can be illustrated as follows:

6.2.4.2 Preliminary Data Diagnostics

6.2.4.2.1 Addressing Correlations and Interactions

The first step in the preliminary checks on data is to detect and address any existing multi-colinearity or possible interactions in the predictor variables of the developed models. The matrix scatter plot is simulated for all predictor variables vs. the response factor to detect the correlation. Scatter plot representation is significant in detecting the linearity of data or any other correlation between predictors and response variables, as well as among predictor variables themselves.

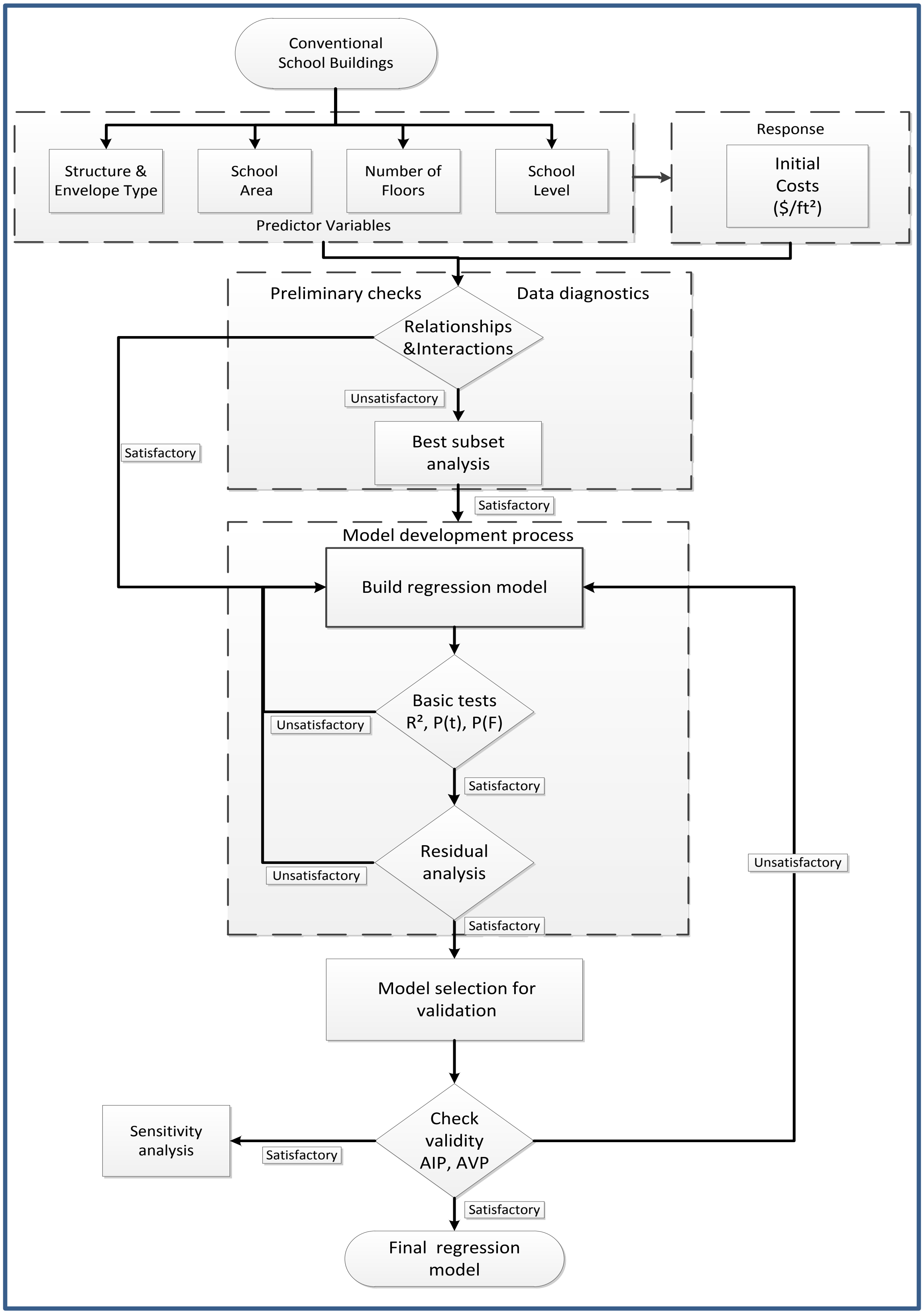


Figure 6.3 Regression model development process

6.2.4.2.2 Best Subset Analysis

The next step in the preliminary diagnosing of data is to perform best subsets' regression analysis. This test identifies the best possible combination of predictors with regards to the highest R^2 and R^2 (adjusted) values and the lowest error and variation values. Hence, the best-fit regression models that can be developed with the specified number of variables are determined using best subset regression analysis.

6.2.4.3 Building Regression Models

After detecting the correlation and identifying the best data subset, seven regression models are developed out of the best data set using RS Means. These models are developed to enable school boards to predict the initial costs of new conventional school buildings associated with applying various structure and envelope types. These regression models are built to be best-fitted to the data at hand, and also to be simple and easily applied by decision makers on school boards.

The computed data is stored in Microsoft Excel due to the versatility of spreadsheet analysis. The Minitab® statistical software package was selected for developing the various regression models. The corresponding data for the deformed variables is installed in Minitab® for regression analysis.

The output from Minitab® consists of constructed regression equations with an estimate of regression coefficients "β_k" for the analyzed data.

6.2.4.4 Preliminary Tests for Model Adequacy

The preliminary tests of the regression models include: coefficient of multiple determinations (R^2), a regression relation test (F), and a (t) test for each regression parameter's coefficient "β_k". The R^2 value measures the predictor variables' variance, or the fitting of data in correlation to "initial costs" (response variable), while the R^2 (adjusted) accounts for the number of predictors in the model. Both values should indicate that the model fits the data well.

The second test is the regression relation test (F). To determine P (F) for the whole model, a hypothesis test is applied. The assumption of the null hypothesis (H_0) is that all regression coefficients, β_0, β_1… β_{p-1} are zero i.e. $\beta_0 = \beta_1 = \beta_{p-1} = 0$. The assumption of the alternate hypothesis (H_a) is that not all coefficients are equal to zero. If the p-value (statistical significance) is 0.00, it means that the null hypothesis is rejected. This hypothesis proves that the estimated model is significant at an α - level of 0.05, indicating that at least one coefficient in the developed regression model is not equal to zero.

The third test is to verify if all of the predictors are significantly corresponded to the response variable or not. "t-tests" are performed individually to determine the validity of regression coefficient, and are performed separately for β_0, β_1… β_{p-1} in a similar fashion. In the case of β_0, the null hypothesis (H_0) of the t-test assumes that $\beta_0 = 0$; while the alternative hypothesis (Ha) assumes that $\beta_0 \neq 0$.

6.2.4.4.1 Residual Analysis

After diagnosing the coefficients and bases satisfactorily, the next step is to analyze the residuals and their patterns. Checking the normality of error is performed to verify the linearity correlation assumptions. Normal probability and frequency is represented in a plotted graph in the developed models in order to perform the residual analysis.

6.2.4.5 Testing the Regression Model's Validity

The first step in the validation is to compare the actual observation with the predicted values for the validation data for each developed model. This validation is performed using the excluded 20% data points and plotted to compare the prediction model with the observed data in hand. The mathematical validation method is performed using the average validity and invalidity percent. Average invalidity and validity percent is computed in this study for data validation using the following formulae (Zayed and Halpin 2005):

$$AIP = \frac{\sum_{i=1}^{n} \left| 1 - \left(\frac{E_i}{C_i} \right) \right|}{n} \qquad \text{(Equation 6.1)}$$

and $$AVP = 1 - AIP \qquad \text{(Equation 6.2)}$$

where AVP is the average validity percent, AIP is the average invalidity percent, E_i is the Predicted Value, C_i is the Actual Value, and n is the number of observations. The AIP value varies from 0 to 1.

6.2.5 Developed Regression Models

Seven multi-regression models are developed in this study to predict the square footage initial costs for new conventional school buildings. Each model is developed to predict the specified structure and envelope type with regards to correlated predictor variables that include: school area (square foot), number of floors (which ranges from1-4), and school level, which ranges from 1-3: elementary school (1), middle school (2), and high school (3). The process of model development is applied to the entire range of prediction models and can be explained below:

6.2.5.1 Wood Structure with Concrete Brick Walls Model (WC)

6.2.5.1.1 Correlation Tests

The first step is to test the linearity of the data by detecting the possible correlation from the obtained scatter plot matrix and the correlation matrix with the transformed Y´ variable; these plots are presented in Figure 6.4.

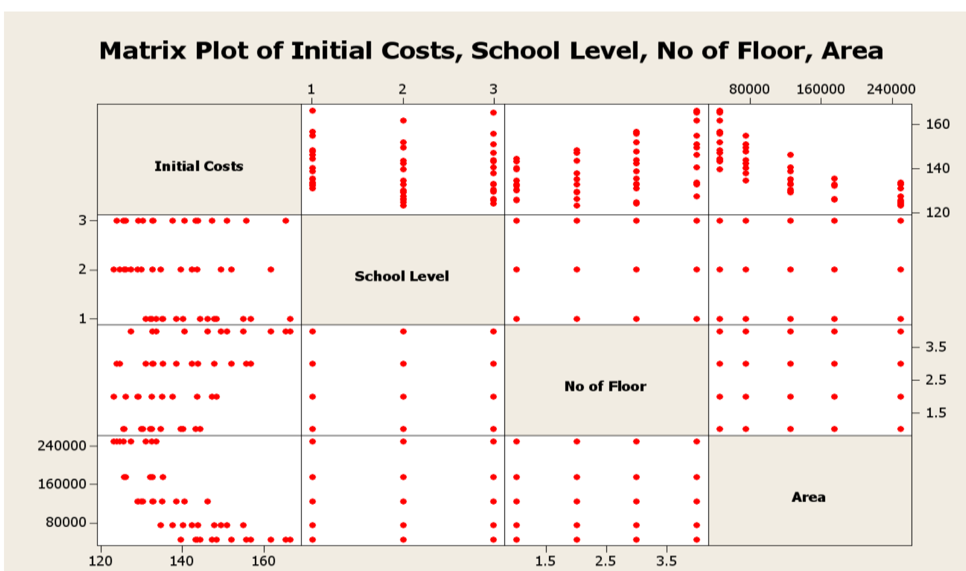


Figure 6.4 scatter matrix plot for regression model parameters

The plots' representation shows that the data is constant and distributed evenly across the graph without forming any pattern. All of these plots indicate that each of the predictor variables is nearly linearly associated with the response variable and so the plots are considered satisfactory.

6.2.5.1.2 Best Subset Analysis

The output of subset regression analysis generates various regression models in each line, as shown in table 6.6. In the WC regression model, the highest values of R^2 and R^2 (adjusted) are recorded at 82.0% and 80.8% respectively, while the lowest values of C_p and standard deviation (S) are recorded at 4.0 and 5.0, respectively. The result of the best subset analysis proves that all predictors are significant and should be combined and included in the developed regression model. This combination of variables is proven to be the best case in all seven of the developed regression models.

Table 6.6 Best subset analysis result using Minitab

Vars	R-Sq	R-Sq(adj)	Mallows Cp	S	Area	No of Floor	School Level
1	61.6	60.8	49.8	7.1487	X		
1	19.6	17.8	152.4	10.344		X	
2	79.0	78.1	9.3	5.3445	X	X	
2	64.9	63.4	43.6	6.9060	X		X
3	82.0	80.8	4.0	5.0061	X	X	X

WC Model:

$$IC(WC) = 148 - 0.000123 \times Area + 4.17 \times No. of\ floor - 2.39 \times School\ level \quad \text{(Equation 6.3)}$$

Where:
IC: Predicted initial costs,
WC: Wood structure with concrete brick walls
Area: School area in square feet
Number of floors: Ranges between 1-4 floors
School level: elementary school (1), middle (2), and high school (3)

Table 6.7 Statistical diagnostic of the WC model

Predictor	Coefficient	SE Coef.	T	P
Constant	148.494	2.902	51.18	0.000
Area	-0.00012269	0.00001009	-12.16	0.000
No of Floor	4.1745	0.6469	6.45	0.000
School Level	-2.3922	0.8861	-2.70	0.010

S = 5.00609 , R-Sq = 82.0% , R-Sq(adj) = 80.8%

Table 6.8 Analysis of Variance of WC model

Source	DF	SS	MS	F	P
Regression	3	5018.2	1672.7	66.75	0.000
Residual Error	44	1102.7	25.1		
Total	47	6120.9			

6.2.5.1.3 Tests of Model Adequacy

The developed model shows that a positive correlation is detected and that the number of floors variable is linked to the response variable (initial costs). On the other hand, a negative relationship is correlated between school area and school level with the predicted initial costs.

1. **Test of R^2 and R^2 (adjusted)**

The result of the preliminary tests shows that R^2 and R^2 (adjusted) values are recorded at 82.0% and 80.8%, respectively. The R^2 value indicates that the predictor variables explain 82.0% of the variance in the response variable (initial costs) for the WC model. The R^2 (adjusted) value is a modification of R^2 that adjusts for the number of explanatory terms in a model. The standard deviation of data (S) is recorded at 5.00. These R^2 values indicate that the data fits well in the built model.

2. **t-tests**

This test is performed to test if all predictors are significantly correlated to the response variable. The p-values for the estimated coefficients for predictors “School area” and “No. of floors” are 0.000 as presented in table 6.7. Similarly, the p-value for predictor “School level” is 0.010. As a result, the null hypothesis is rejected and the alternative hypothesis is accepted. This indicates that the predictors are significantly correlated to the response variable “initial costs” at an α - level of 0.1.

3. **F-Test**

The p-value (statistical significance) in the analysis of variance is 0.000 as shown in table 6.8. The null hypothesis is thus rejected. This shows that the estimated model is significant at an α - level of 0.05. Consequently, at least one coefficient in the developed regression model is not equal to zero.

4. **Residual Analysis (Normality of Errors)**

The normal probability plot indicates that error terms are approximately normally distributed. Minor departures from normality are observed as presented in both graphs; the normal probability plot and the histogram of residuals plot. These departures are considered as unusual possible outliers. R^2 values and other statistical parameters could be improved by eliminating these outliers; however, the model would not be the best representation of the real world data in hand. The result of the residual analysis is satisfactory since a few minor departures from normality do not indicate any serious problems (Kutner et al 2005).

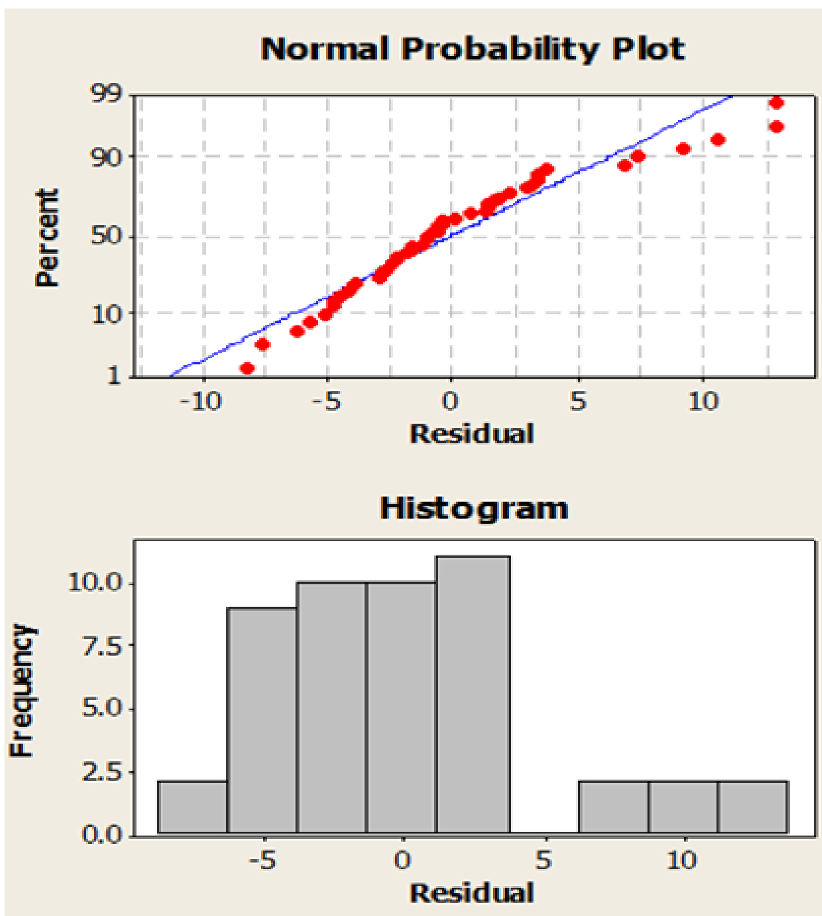


Figure 6.5 Normal probability plot and histogram resulted from Residual analysis

6.2.5.1.4 WC Model Validation

1. **Plot Validation Method**

Figure 6.6 presents the plot validation method for the actual observation vs. predicted output plot. This representation indicates that the predicted values are scattered around the actual values for the response variable. Therefore, the first validation test's results are considered to be satisfactory.

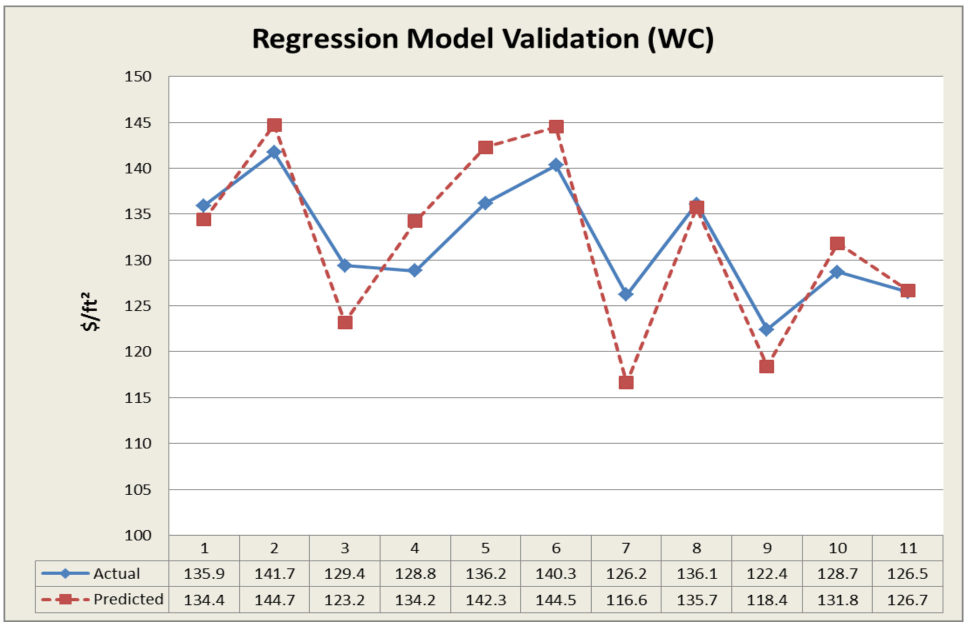


Figure 6.6 Plot validation for the WC regression model

2. **Mathematical Validation**

$$AIP = \frac{\sum_{i=1}^{n} \left| 1 - \left(\frac{E_i}{C_i} \right) \right|}{n} = AIP = \frac{0.3339}{11} = 0.0303 \ , \quad AVP = 1 - AIP = 0.9696$$

The value of validation indicates that the predicted model is almost 96.9% accurate. The final validation results can be considered to be more than satisfactory because the WC model explains about 96.9% of the variation in the validation data.

6.2.5.2 Wood Structure with Wood Studs Walls Model (WW)

$$IC(WW) = 145 - 0.000095 \times Area + 1.92 \times No.of\ floors - 2.4 \times School\ level \qquad \text{(Equation 6.4)}$$

Table 6.9 Statistical diagnostic of the WW model

Predictor	Coefficient	SE Coef.	T	P
Constant	144.787	2.352	61.55	0.000
Area	-0.00009510	0.00000818	-11.62	0.000
No of Floor	1.9224	0.5244	3.67	0.001
School Level	-2.3975	0.7183	-3.34	0.002

S = 4.05825 R-Sq = 78.4% R-Sq(adj) = 77.0%

Table 6.10 Analysis of the Variance of the WW model

Source	DF	SS	MS	F	P
Regression	3	2635.61	878.54	53.34	0.000
Residual Error	44	724.65	16.47		
Total	47	3360.26			

WW Model Validation

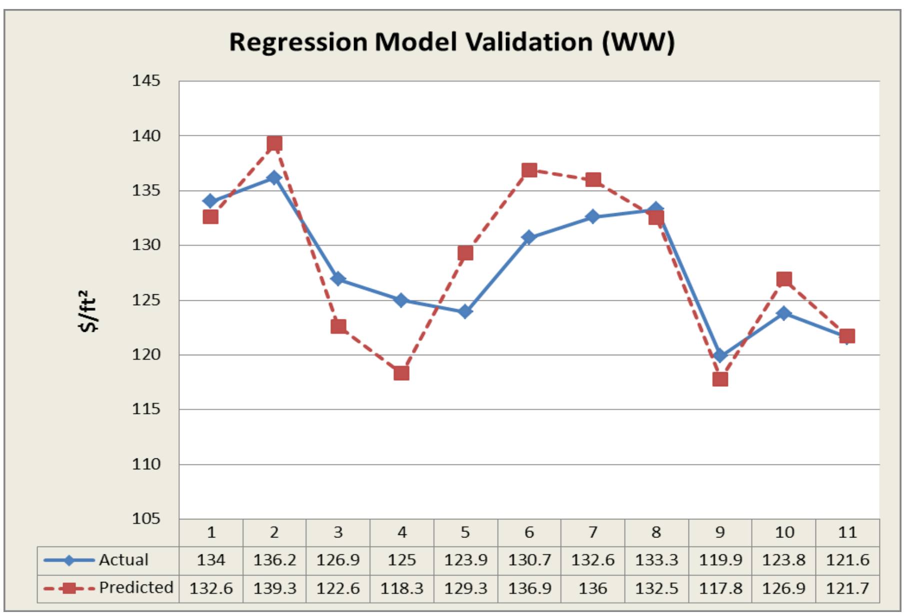


Figure 6.7 Figure 6.7: Plot validation for WW regression model

- AIP = 0.0259 , AVP = 0.9740

6.2.5.3 Steel Structure with Steel Studs Wall Model (SS)

$$IC(SS) = 159 - 0.000081 \times Area + 2.72 \times No.of\ floors - 2.38 \times School\ level \quad \text{(Equation 6.5)}$$

Table 6.11 Statistical diagnostic of the SS model

Predictor	Coefficient	SE Coef.	T	P
Constant	159.421	2.513	63.45	0.000
Area	-0.00008081	0.00000874	-9.25	0.000
No of Floor	2.7215	0.5602	4.86	0.000
School Level	-2.3823	0.7673	-3.10	0.003

S = 4.33486   R-Sq = 73.2%   R-Sq(adj) = 71.4%

Table 6.12 Analysis of the Variance of the SS model

Source	DF	SS	MS	F	P
Regression	3	2257.45	752.48	40.04	0.000
Residual Error	44	826.81	18.79		
Total	47	3084.26			

SS Model Validation

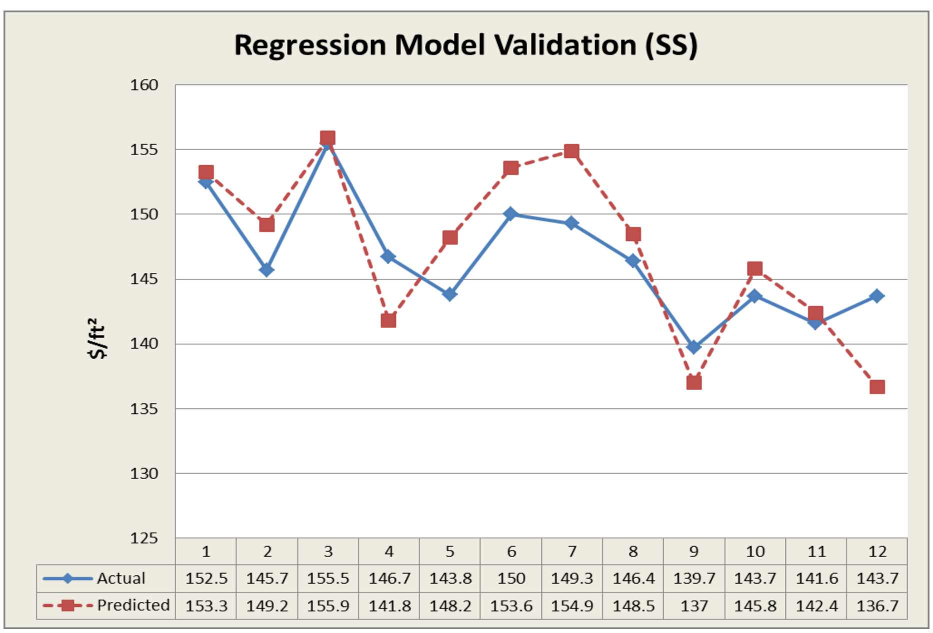


Figure 6.8 Plot validation for SS regression model

- AIP = 0.0220, AVP = 0.9780

6.2.5.4 Steel Structure with Exterior Brick Model (SC)

$$IC(SC) = 164 - 0.000115 \times Area + 5.48 \times No.of\ floors - 3.38 \times School\ level$$
(Equation 6.6)

Table 6.13 Statistical diagnostic of the SC model

Predictor	Coefficient	SE Coef.	T	P
Constant	163.658	3.236	50.58	0.000
Area	-0.00011465	0.00001126	-10.19	0.000
No of Floor	5.4827	0.7214	7.60	0.000
School Level	-2.3781	0.9881	-2.41	0.020

S = 5.58261   R-Sq = 79.6%   R-Sq(adj) = 78.2%

Table 6.14 Analysis of the Variance of the SC model

Source	DF	SS	MS	F	P
Regression	3	5343.9	1781.3	57.16	0.000
Residual Error	44	1371.3	31.2		
Total	47	6715.2			

SC Model Validation

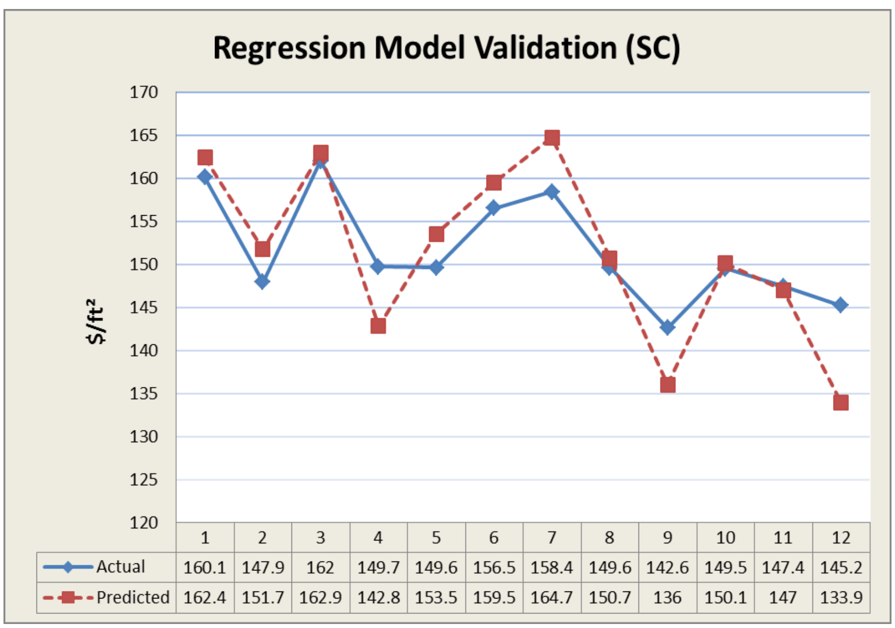


Figure 6.9 Plot validation for regression of the SC model

- AIP = 0.0263, AVP = 0.9737

6.2.5.5 Steel Structure with Wood Stud Walls Model (SW)

$$IC(SW) = 160 - 0.000087 \times Area + 3.16 \times No.of\ floors - 2.29 \times School\ level \quad \text{(Equation 6.7)}$$

Table 6.15 Statistical diagnostic of SW model

Predictor	Coefficient	SE Coef.	T	P
Constant	159.881	2.615	61.14	0.000
Area	-0.00008700	0.00000908	-9.58	0.000
No of Floor	3.1598	0.5803	5.45	0.000
School Level	-2.2936	0.7970	-2.88	0.006

S = 4.49288 R-Sq = 74.1% R-Sq(adj) = 72.4%

Table 6.16 Table 6.16: Analysis of Variance of SW model

Source	DF	SS	MS	F	P
Regression	3	2544.89	848.30	42.02	0.000
Residual Error	44	888.18	20.19		
Total	47	3433.07			

SW Model Validation

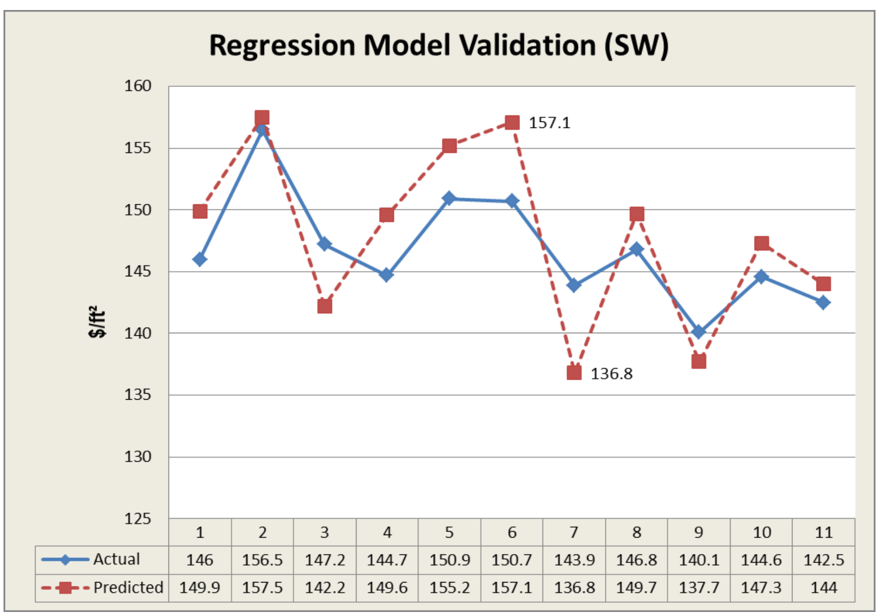


Figure 6.10 Plot validation for regression SW model

- AIP = 0.0262, AVP = 0.9740

6.2.5.6 Concrete Structure with Cavity Walls Model (CM)

$$IC(CM) = 182 - 0.000158 \times Area + 5.14 \times No.of\ floor - 2.72 \times School\ level \quad \text{(Equation 6.8)}$$

Table 6.17 Statistical diagnostic of CM model

Predictor	Coefficient	SE Coef.	T	P
Constant	182.311	4.992	36.52	0.000
Area	-0.00015778	0.00001736	-9.09	0.000
No of Floor	5.140	1.113	4.62	0.000
School Level	-2.722	1.524	-1.79	0.081

S = 8.61204 R-Sq = 71.3% R-Sq(adj) = 69.3%

Table 6.18 Analysis of the Variance of the CM model

Source	DF	SS	MS	F	P
Regression	3	8089.8	2696.6	36.36	0.000
Residual Error	44	3263.4	74.2		
Total	47	11353.2			

CM Model Validation

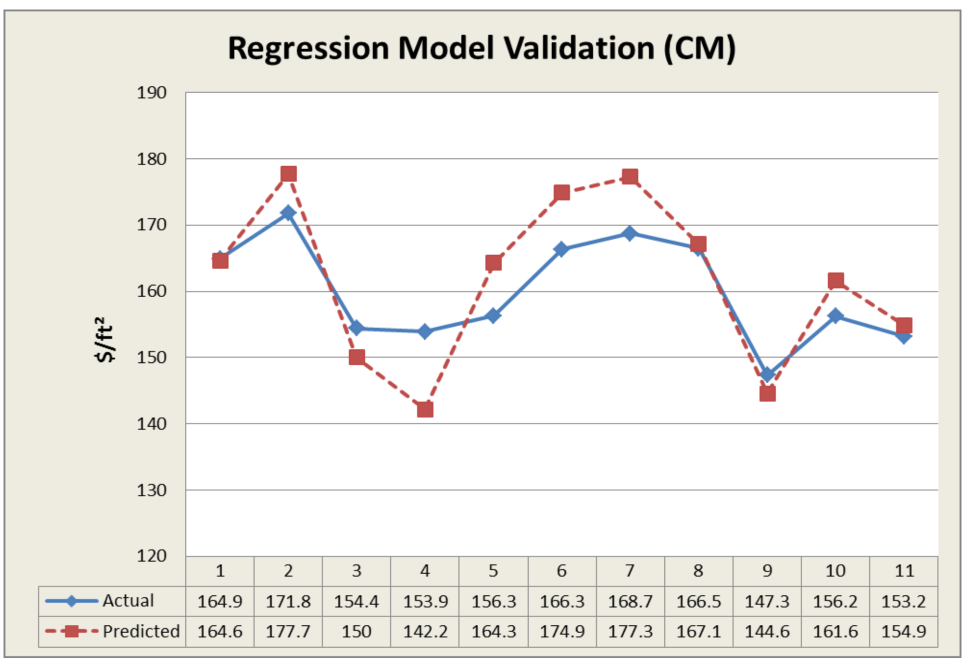


Figure 6.11 Plot validation for regression in the CM model

- AIP = 0.0329, AVP = 0.9671

6.2.5.7 Concrete Structure with Precast Concrete Panels Model (CC)

$$IC(CC) = 188 - 0.000208 \times Area + 8.64 \times No.of\ floors - 2.24 \times School\ level \qquad \text{(Equation 6.9)}$$

Table 6.19 Statistical diagnostic of CC model

Predictor	Coefficient	SE Coef.	T	P
Constant	188.294	6.109	30.82	0.000
Area	-0.00020795	0.00002116	-9.83	0.000
No of Floor	8.639	1.340	6.45	0.000
School Level	-2.241	1.842	-1.22	0.230

S = 10.5407 R-Sq = 75.9% R-Sq(adj) = 74.2%

Table 6.20 Analysis of the Variance of the CC model

Source	DF	SS	MS	F	P
Regression	3	15705.4	5235.1	47.12	0.000
Residual Error	45	4999.8	111.1		
Total	48	20705.2			

CC Model Validation

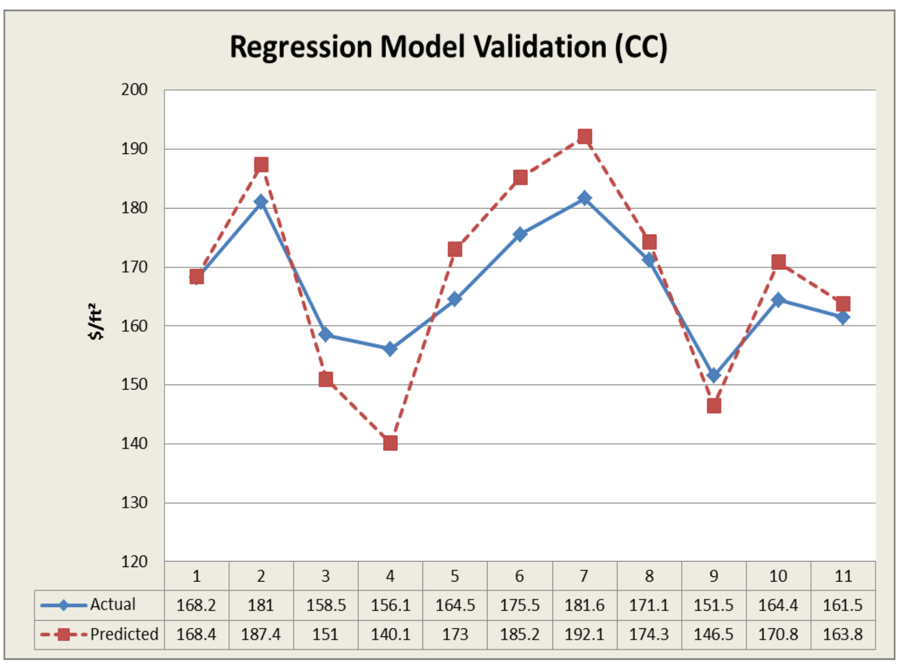


Figure 6.12 Plot validation for regression CC model

- AIP = 0.0413 , AVP = 0.9587

6.3 Energy Costs (Conventional Schools)

6.3.1 Energy Simulation and Costs Process

The energy performance of the various envelope systems is measured by performing hourly energy simulations in climate zone 6a (Montreal) to calculate the monthly electricity and natural gas consumption. The energy simulation is carried out with (eQUEST) software, developed by the US Department of Energy (DOE) to measure the energy performance of various building types and exposure systems. This simulation is performed based on identifying some energy input parameters that affect the energy consumption of school buildings and their overall energy costs.

Figure 6.12 presents the energy cost estimating process. The process consisted of four major stages; defining the energy parameters, performing energy simulations, computing energy consumption, and estimating the total energy costs.

The energy parameters are identified through the eQUEST building creation wizard (schematic design wizard). These parameters include general project information (city, area, number of floors), building footprint (form and floor plan), envelope description (roofs, exterior walls), interior construction (floors, ceilings), exterior openings (windows, glazing, skylights), activity area allocation (space distribution), internal energy loads (lighting, plug loads), main schedule information (operating schedule), HVAC description (source, temperature, fans), and water heating system (source, temperature, pumping, and storage tanks).

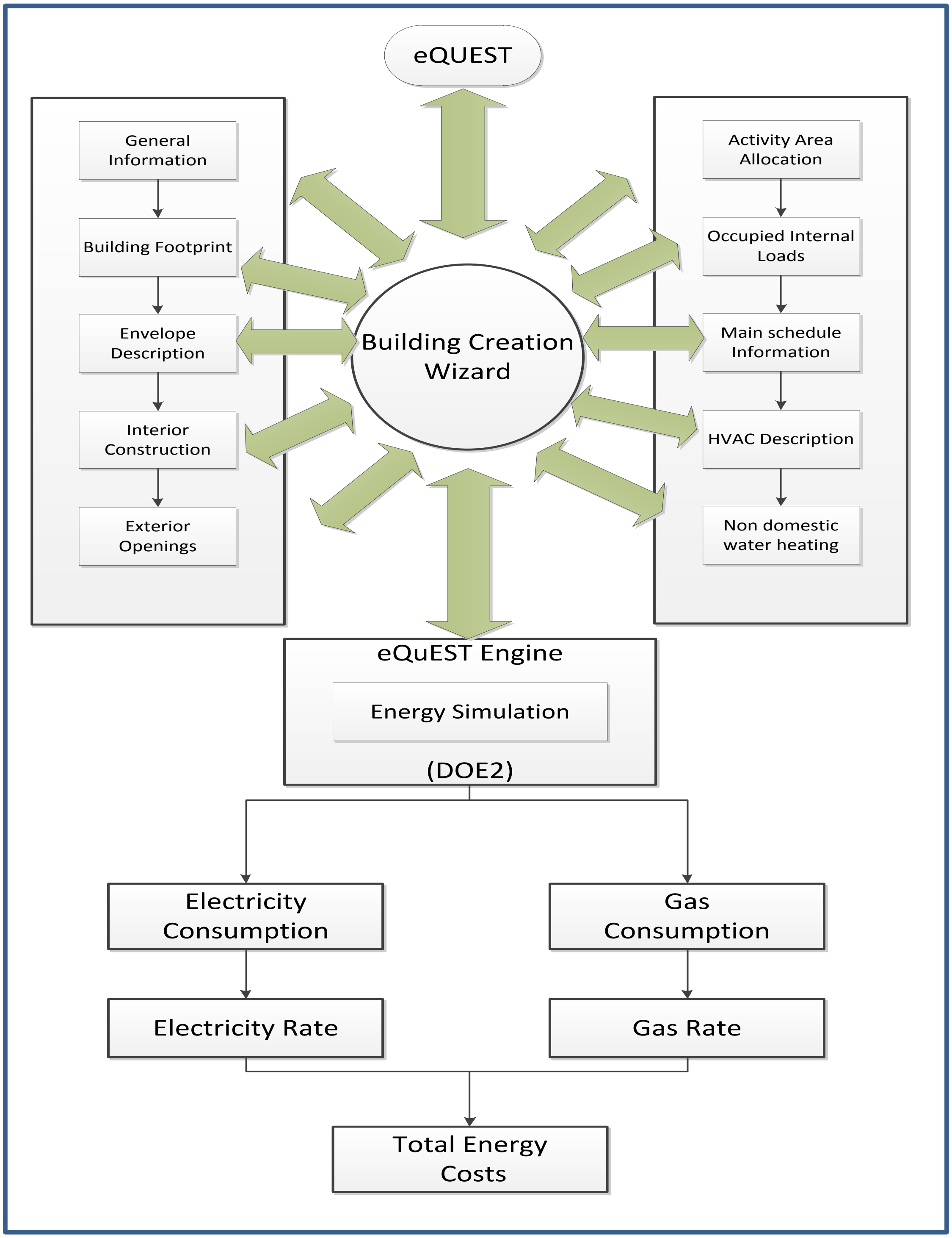


Figure 6.13 Energy simulation using the eQUEST & energy estimating process

Since school buildings are unique in their function, occupancy, and characteristics, and because different school levels have different size areas, characteristics, numbers of users, and internal loads, energy prototype models are developed for elementary and high school buildings in Canada using ASHRAE 90.1 and ASHRAE 62 to compute the energy costs.

6.3.1.1 Energy Prototype Models

6.3.1.1.1 Prototype Model for an Elementary School

A 75,000 ft^2 prototype model is developed for a one story elementary school building in Montreal to measure the energy consumption and costs for the various envelope types for a conventional elementary school building. The capacity of the tested elementary school is about 700 students. The plan configuration is H- shaped, which provides 33% fenestration to gross wall area in the classrooms. This percentage is determined based on ASHRAE 90.1 to meet the expected window area needed to provide adequate daylighting to the classrooms. The fenestration is applied equally over all of the exterior facades without no overhangs or fin systems.

6.3.1.1.2 Prototype Model for a High School

A 250,000 ft^2 prototype model is developed for a three story school building in Montreal to calculate the energy costs for the various envelope types of conventional high school buildings. The capacity of the tested high school is about 1500 students. The orientation of the long axis of the H-shaped building is oriented north-south. The modeled prototype height is 13.1ft floor to floor, 9.0 ft ceiling to floor height, and 3.6 ft window sill height, as shown in Table 6.21.

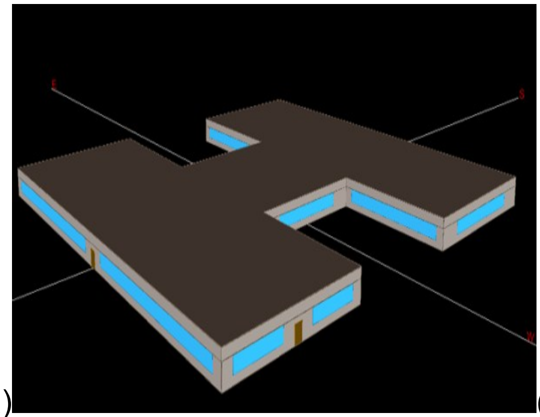
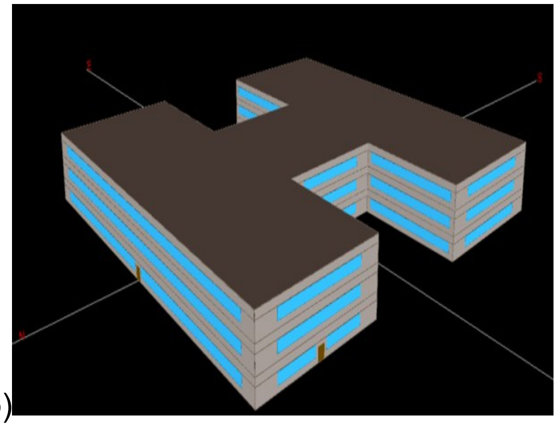
(a)  (b) 

Figure 6.14 (a) elementary school prototype model, (b) high school model

Table 6.21 Prototype models' description applying ASHRAE 90.1 recommendations

Items	**Prototype Characteristic**	
School type	Elementary school	High school
Total gross area	75,000 ft²	250,000 ft²
No. of floors	1 floor	3 floors
Number of students	700	1500
Building orientation	Long Axis oriented (North-South)	
Floor height	13.1 ft	
Floor to ceiling height	9.0 ft	
Windows area	33% fenestration to gross wall area	
Glazing sill height	3.6 ft	
Plan configuration	H- shape	
Location (city)	Montreal, Canada	
Climate zone	6a (Cold- Dry)	
Percent conditioned	Fully heated and cooled	
Thermal transmittance of window	U – (0.42) (btu/h-ft-°F)	
Solar heat gain coefficient	(SHGC)-0.40 (btu/h-ft-°F)	
Infiltration Ext wall area (perimeter)	0.038 CFM/ ft²	
Infiltration floor area (core)	0.001 CFM/ ft²	
Heating equipment	Hot water coils	
Cooling equipment	Chilled water coils	
Analysis year	2011	
Code	ASHRAE 90.1, ASHRAE 62	

6.3.1.2 Building Envelopes

The purpose of the energy simulation is to measure the energy performance of each envelope type for a school building and to compare it to others. These alternatives include: steel stud wall, wood stud wall, steel stud with exterior brick, wood stud with exterior brick, steel with exterior wood, precast concrete panels, and masonry wall (face brick with concrete block back-up). Four types of roof are applied in this study: solid concrete roof applied on masonry walls, hollow core slab applied on precast walls, built-up metal deck roof applied on steel stud walls, and wood/play wood roof on wood frame applied on wood stud walls either with or without exterior brick. Thermal properties of the envelopes are in compliance with the minimum requirement by the National Energy code of Canada for Buildings, as shown in Tables 6.22 and 6.23

Table 6.22 Wall Layer specifications for the different alternatives (NECB, 1997)

No.	**Wall Type**	Thickness (mm)	Insulation Type	Total Thickness (mm)	Conductivity U- value (btu/h-ft-°F)
1	Pre cast wall	200	Board Insulation (Preformed mineral board , 2 Inch (IN23) U(0.024) (btu/h-ft-°F)	257	U(0.073)
2	Masonry (Cavity Wall)	250		307	U(0.098)
3	Steel Stud	107		107	U(0.142)
4	Wood Stud	107		107	U(0.120)
5	Steel + Masonry brick	150		157	U(0.115)
6	Wood + Masonry brick	150		157	U(0.109)
7	Steel + Wood Stud	107		107	U(0.120)

Table 6.23 Roof layer specifications for the different alternatives (NECB, 1997)

No.	**Roof Type**	Thickness (mm)	Insulation Type	Total Thickness (mm)	Conductivity U- value (btu/h-ft-°F)
1	Solid concrete slab	150	Board Insulation (polystyrene , Expanded,3 Inch (IN36) U(0.020) (btu/h-ft-°F)	240	U(0.055)
2	Hollow- core slab	150		240	U(0.050)
3	Wood roof – Wood truss	75		150	U(0.069)
4	Metal deck– steel joist	75		150	U(0.076)

Other energy parameters are described in the data collection chapter and in the sustainability assessment models.

6.3.2 Energy Simulation Results

6.3.2.1 Energy Consumption, Elementary School

Energy simulation of the prototype model indicates that electricity consumption used in space cooling and internal loads has no significant difference in values for most alternatives. In contrast, the gas consumption for space heating during winter shows a significant variation. The average annual electricity consumption for the elementary school is 11.36 (kWh/ft^2) while the natural gas consumption ranges between (53.88–62.59) kBtu/ft^2. The lowest electricity consumption is observed for a concrete envelope (CC), with total annual saving of 1500 kWh over the highest-consuming option, steel siding facades (SS). The minimum total gas consumption is recorded at 4.04 million kBtu for the concrete envelope, while the maximum consumption is recorded at 4.69 million kBtu for steel siding facades. Annual saving of 650,000 kBtu in gas consumption is recorded when a concrete envelope is applied, as presented in Table 6.24.

Table 6.24 Annual energy consumption for the conventional elementary school

Elementary	Total Annual Energy Consumption		Annual Energy Consumption / ft^2	
Alternative	Electricity (Kwh)	Gas (kBtu)	Electricity (Kwh/ft^2)	Gas ($kBtu/ft^2$)
(WW)	852,490	4,516,200	11.36	60.21
(WC)	852,290	4,483,800	11.36	59.78
(SS)	852,980	4,694,500	11.37	62.59
(SC)	852,360	4,599,200	11.36	61.32
(SW)	852,490	4,516,200	11.36	60.21
(CM)	852,160	4,152,900	11.36	55.37
(CC)	851,480	4,041,500	11.35	53.88

6.3.2.2 Energy Consumption, High School

Table 6.25 presents the annual energy consumption for a high school building in Montreal. Energy simulation results indicate that the square footage electricity consumption, at 13.14 $kWh/ft^{2,}$ is higher for a high school than for an elementary school (11.36) kWh/ft^2. However, the annual gas consumption is lower for a high school, ranging from 46 to 51.2 $kBtu/ft^2$ compared to gas consumption for an elementary school, which ranges from 53.88 – 62.59 $kBtu/ft^2$. The lowest electricity consumption is observed for a concrete envelope (CC), with total annual saving of 4100 kWh over the highest consumer, steel siding facades (SS). The minimum total gas consumption is recorded at 11.5 million kBtu for a concrete envelope, while the maximum consumption is recorded at 12.8 million kBtu for steel siding facades. Annual saving of 1.3 million kBtu in gas consumption is recorded when a concrete system is applied, as presented in table 6.25.

Table 6.25 Annual energy consumption for a conventional high school

High School	Total Annual Energy Consumption		Annual Energy Consumption / ft^2	
Alternative	Electricity (Kwh)	Gas (kBtu)	Electricity (Kwh/ft2)	Gas ($kBtu/ft^2$)
(WW)	3,285,300	12,410,000	13.14	49.64
(WC)	3,284,900	12,310,000	13.13	49.24
(SS)	3,286,400	12,800,000	13.15	51.20
(SC)	3,285,000	12,490,000	13.14	49.96
(SW)	3,285,300	12,410,000	13.14	49.64
(CM)	3,284,600	11,860,000	13.13	47.44
(CC)	3,283,300	11,500,000	13.13	46.00

6.3.3 Results of Energy Costs

Energy costs are calculated in this research according to the current prices of electricity and natural gas as presented to school buildings in the City of Montreal. The rate of electricity utilization is about \$0.096/kWh, provided by Hydro Quebec, and the natural gas price is \$0.529/$M^{3,}$ provided by Gaz Metro. The results of the energy simulation are multiplied by the utility rates to calculate the total energy costs.

6.3.3.1 Energy Costs for an Elementary School

Table 6.26 presents the total electricity and natural gas costs for an elementary school. The average of the annual electricity cost for a one-floor elementary school with an area of 75,000 ft^2 is about \$ 82,050, while the cost of natural gas ranges from\$58,900 - \$68,450.

Table 6.26 Annual energy costs for a conventional elementary school

Elementary	Energy costs by sources		Total Annual Energy Costs	
Alternative	Annual electricity costs (CAD$)	Annual gas costs (CAD$)	Total annual energy cost	Energy costs ($/ft^2)
(WW)	$82,100	$65,850	$147,950	$1.973
(WC)	$82,050	$65,350	$147,400	$1.965
(SS)	$82,100	$68,450	$150,550	$2.007
(SC)	$82,050	$67,050	$149,100	$1.988
(SW)	$82,100	$65,850	$147,950	$1.973
(CM)	$82,050	$60,550	$142,600	$1.901
(CC)	$81,950	$58,900	$140,850	$1.878

Figure 6.14 shows the total annual energy costs associated with applying different envelopes to elementary school buildings. The minimum energy cost is recorded at $140,850 for concrete exposure (CC) while the maximum value is $150,550 for steel exposure (SS). The expected annual energy cost saving is about $10,000 for a 75,000ft^2 elementary school building. The second-lowest cost is recorded at $142,600 for a masonry school building (CM), while the next-highest cost is $149,100 for the steel with exterior brick (SC) option. The energy costs for wood exposure are recorded at $147,400 and $147,950 for WC) and WW, respectively.

To sum up, a significant savings in energy cost is obtained when a concrete envelope is used in an elementary school. This savings be quite valuable since there is such a large scale of school buildings. For example, $100 million could be saved annually for 10,000 elementary schools in Canada by applying concrete envelopes.

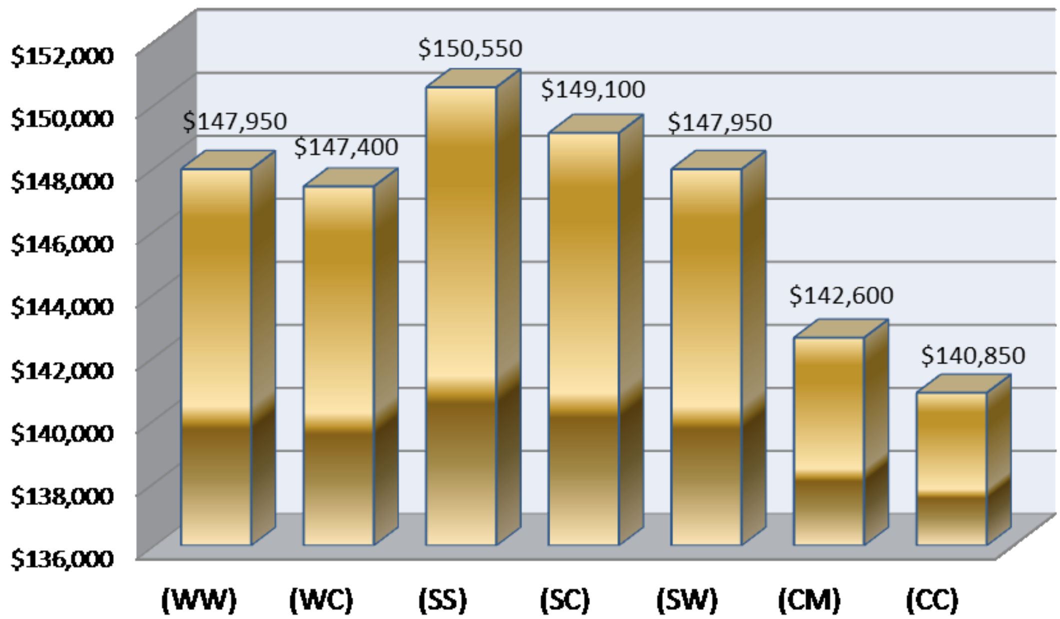


Figure 6.15 Total annual energy costs for a conventional elementary school

6.3.3.2 Energy Costs for a High School

Table 6.27 presents the total electricity and natural gas costs for a high school. The average of the annual electricity cost for a three story high school with an area of 250,000 ft^2 is about $ 316,300, while the cost of natural gas ranges from $167,600 to $186,600.

Table 6.27 Annual energy costs for a conventional elementary school

High school	Energy costs by sources		Total annual energy costs	
Alternative	Annual electricity costs (CAD$)	Annual gas costs (CAD$)	Total annual energy cost	Energy costs ($/ft^2)
(WW)	$316,300	$180,900	$497,200	$1.989
(WC)	$316,250	$179,500	$495,750	$1.983
(SS)	$316,400	$186,600	$503,000	$2.012
(SC)	$316,350	$182,000	$498,350	$1.993
(SW)	$316,300	$180,900	$497,200	$1.989
(CM)	$316,200	$172,900	$489,100	$1.956
(CC)	$316,100	$167,600	$483,700	$1.935

Figure 6.15 shows the total annual energy costs associated with applying different envelopes to high school buildings. The minimum energy cost is recorded at $483,700 for concrete exposure (CC), while the maximum value is observed at $503,000 for steel exposure (SS). The expected annual energy cost saving is about $20,000 for a 250,000ft^2 high school building. The second lowest cost is recorded at $489,100 for a masonry school building (CM), while the next-highest cost is observed at $498,350 for steel with exterior brick (SC). The energy costs for wood exposure are recorded at $495,750 and $497,200 for WC and WW, respectively.

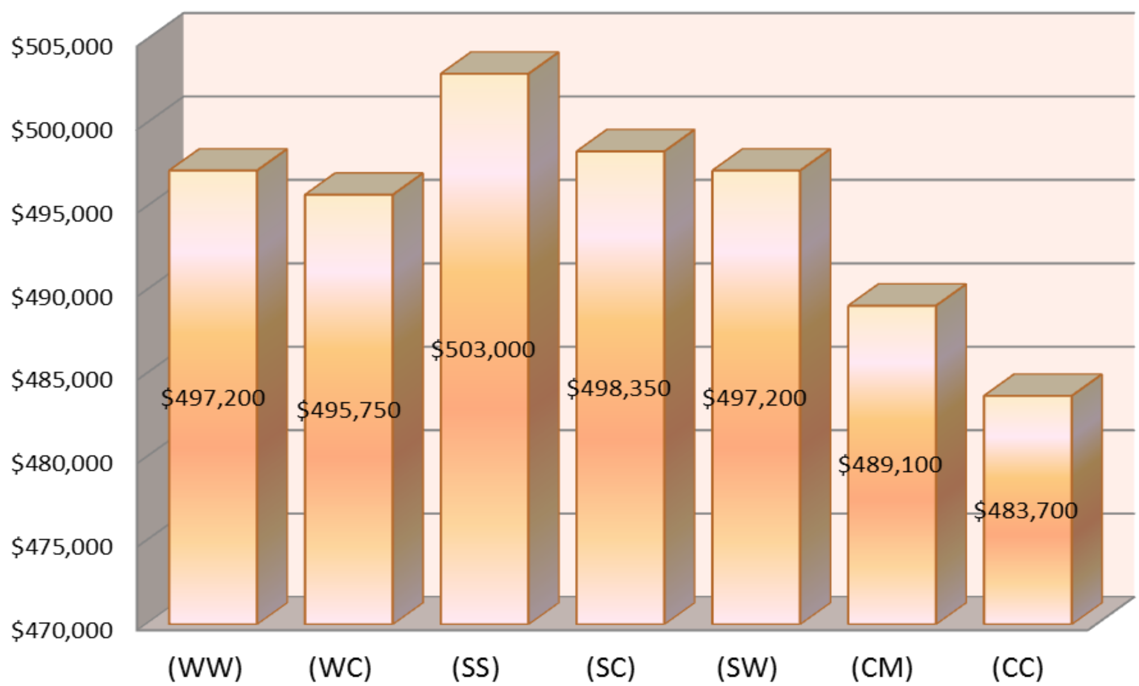


Figure 6.16 Total annual energy costs for a conventional high school

To sum up, a significant savings in energy cost is obtained when a concrete envelope is applied to a high school building. This savings would be remarkable with a large-scale application to school buildings. For example, almost $200 million could be saved annually if 10,000 high schools with similar areas in Canada were constructed with concrete envelopes.

6.4 Major Repairs Costs (MR)

Major repairs include the whole range of structural repairs: floors, exterior walls/columns, chimneys, parapets, exterior doors, exterior steps, stairs, ramps, fire escape, windows, roof and skylights, interior bearing walls and fire walls, other interior walls, floor finishes, ceilings, lockers, interior doors, interior stairs, elevators, escalators, interior electrical distribution, lighting fixtures, communications systems, swimming pool systems, water distribution system, pluming drainage system, hot water heaters, plumbing fixtures. MR also include HVAC systems type, heat generating systems, heating fuel/energy systems, cooling/air conditioning generating systems, HVAC equipment, piped heating and cooling distribution systems, ducted heating and cooling distribution systems, HVAC controlled systems, fire alarm systems, smoke detection systems, fire suppression systems, emergency/standby power systems, emergency/exit lighting systems, interior and exterior routes, general appearance, cleanliness, acoustics, lighting quality, and indoor air quality (NY School Boards, 2005).

6.4.1 Process of Computing Major Repairs Costs

The major repairs cost estimating process for school buildings has seven major stages, as presented in Figure 6.16. The first stage is collecting the data from North American school boards, which comprises 400 school buildings. The next stage is to classify the data, is performed according to many factors such as structure type, school area, number of floors, school level, year of construction, and location (city). Organizing and sorting the data occurs next, based on the time and the cost spent on assets. Since historical major repairs occurred at different time periods, the adjustment of time is done in the subsequent step, in which all historical data will be converted to the present value in order to be used in the prediction model. The next stage is the adjustment of the location to convert the data from different cities to the city of Montreal in order to more realistically compare the performances of various alternatives. The total major repair costs are then calculated for each school building and are divided by the area and age of each building. The final stage indicates the resulted annual major repair costs per square footage, as shown in Figure 6.16.

6.4.1.1 Data Collection

Major repair cost data is gathered from various school boards in North America. This data refers to approximately 400 conventional elementary and high school buildings in two major urban areas, including information regarding 140 wooden school buildings from Los Angeles, 130 steel, and 140 concrete school buildings from 140 different cities in New York State. The data collection for major repairs is presented in the data collection chapter.

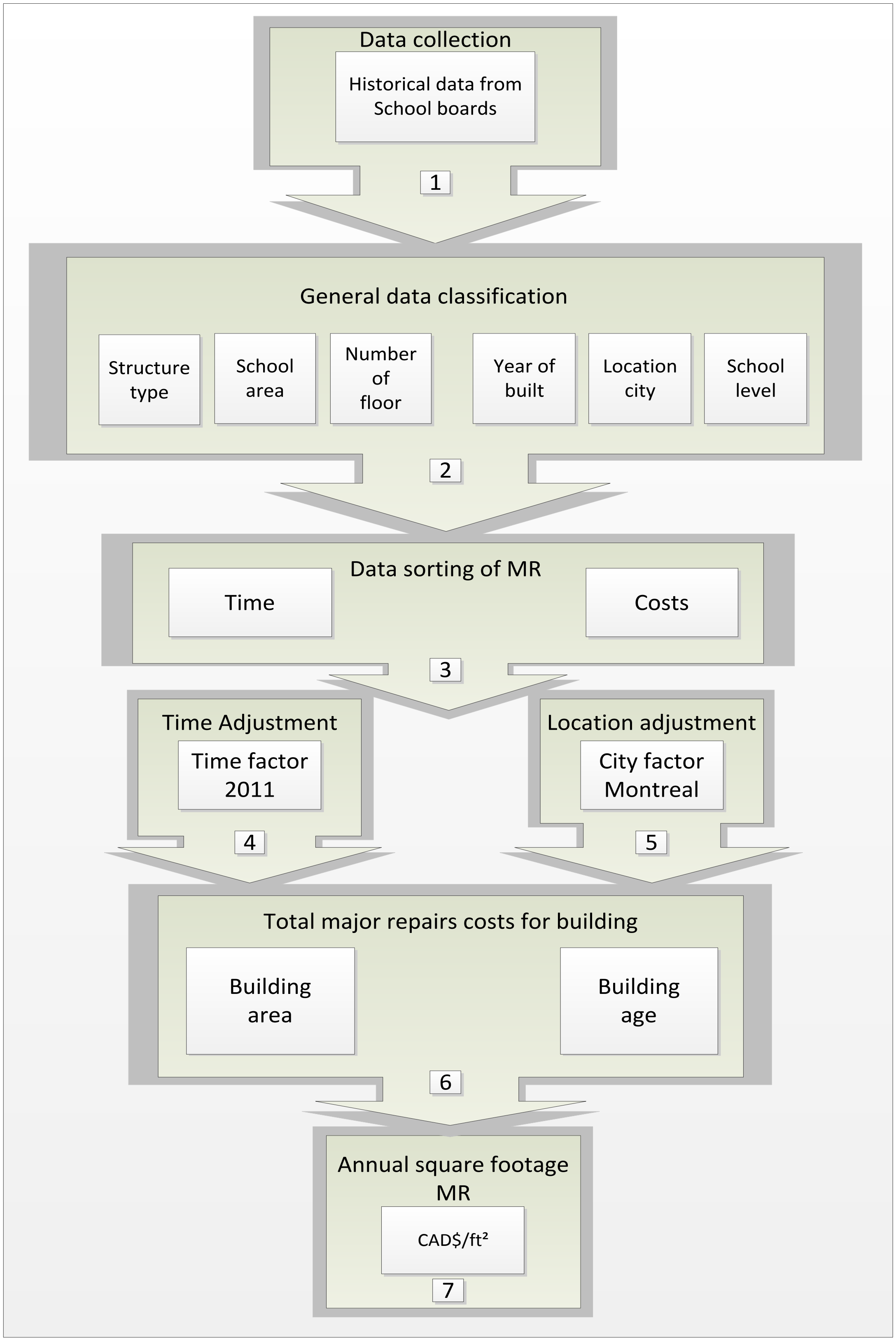


Figure 6.17 Major repair costs computing process

6.4.1.2 General Data Classification

The major repair cost collected data is classified first of all according to structure types: concrete, steel, and wood, as presented in Table 6.28. The location or the city is identified for each building as one of the significant factors that affects the cost and that must be adjusted. School level is defined as elementary or high school and is combined with area size to find the square footage MR costs. Number of floors is also gathered to measure their influence on major repair costs. Finally, year of construction is a significant parameter as the age of the investigated building affects the annual major repair costs.

Table 6.28 General classification method of major repairs costs data

Structure Type	**Wood**	School Type	E
City	**Los Angeles - CA**	Year	**1967**
Area	**47100**	No. Of Floor	**2**
Structure Type	**Concrete**	School Type	**H**
City	**Amsterdam - NY**	Year	**1977**
Area	**221100**	No. Of Floor	**1**
Structure Type	**Steel**	School Type	**E**
City	**Chatham- NY**	Year	**1973**
Area	**88100**	No. Of Floor	**1**

6.4.1.3 Sorting of MR Cost Data

The next stage, after classifying the general data, is sorting the MR cost data using Microsoft Excel. This sorting is performed according to the time of occurrence and the amount of allocated or spent costs. Table 6.29 shows part of a sample of the detailed MR cost dispensed at different time periods. The total of

MR costs in a year is computed, such as the costs spent in the year 2000, as presented in Table 6.29. The total MR costs for each year are then adjusted based on the time index factor.

Table 6.29 Sample of sorting of MR costs data

Year	Major repairs Costs
1997	$49,400
1997 Total	$49,400
Time Factor	$80,983.59
1999	$41,369
1999 Total	$41,369
Time Factor	$65,045.60
2000	$6,400
2000 Total	$6,400
Time Factor	$9,785.93
2001	$59,705
2001	$43,500
2001 Total	$103,205
Time Factor	$148,283.09
2002	$481,022
2002	$12,840
2002 Total	$493,862
Time Factor	$709,572.03

6.4.1.4 Time Adjustment of the MR Costs

All MR costs from different time periods are converted into present-day values for 2011. This time adjustment is done so that the historical data can be used for the LCC prediction models. Table 6.30 presents the time index factors used for MR cost adjustment. The MR cost time adjustment factors are gathered from RS Means.

Table 6.30 Sample of time adjustment index factors (RS Means, 2011)

MR time	Adjusted year	Time Index factor
1997	2011	1.6393
1998	2011	1.6077
1999	2011	1.5723
2000	2011	1.5290
2001	2011	1.4792
2002	2011	1.4367
2003	2011	1.4005
2004	2011	1.2870
2005	2011	1.2210
2006	2011	1.1415
2007	2011	1.0917
2008	2011	1.0256
2009	2011	1.0266
2010	2011	1.0080

6.4.1.5 Location Adjustment of the MR Costs

The MR cost data is collected from various school boards located in various cities in North America. The data is collected from more than 140 cities, most located in New York State. The applied location index factors are for commercial buildings as recommended by RS Means. Some cities have no determined location index factor. Therefore, they are adjusted according to their closest major city. Table 6.31 presents the location adjustment index factors applied for the various cities. All of these cities are adjusted to the city of Montreal in order to be used in LCC prediction model.

Table 6.31 Locations adjustment factors for commercial buildings (RS. Means,2011)

Original city	Closest city	Location index factors
Chatham	Albany	1.0515
Corning	Binghamton	1.0967
Eden	Buffalo	1.0000
Addison	Elmira	1.1086
Baldwin	Far Rockaway	0.7786
Babylon	Hicksville	0.8225
Andover	Jamestown	1.0967
Lagrange	Monticello	0.9444
Bas-Sheva	New York	0.7611
Au Sable Forks	Plattsburgh	1.1086
Patterson	Poughkeepsie	0.9189
Great neck	Queens	0.7846
Avon	Rochester	1.0303
Amsterdam	Schenectady	1.0515
Cazenovia	Syracuse	1.0625
Cooperstown	Utica	1.0851
Bedford	White Plains	0.8571
New City	Yonkers	0.8429
Los Angeles	Los Angeles	0.9444

6.4.1.6 Total MR Costs

After adjusting the time and location of the various costs, the total MR costs of each investigated building are computed accordingly. The total MR costs are calculated for all 400 school buildings. In this stage, the age of each building is used to calculate the total annual MR costs. Furthermore, the total gross area is used to calculate the square footage MR costs. Table 6.32 shows the total MR costs for the various buildings with regards to structure type, age, area, number of floor, and school level.

Table 6.32 Sample of total and annual MR costs for various structure types

Structure	SL	Area	Age	NOF	Total MRC	Annual MRC	MRC ($/ft²)
concrete	E	15700	51	1	$1,289,940	$25,293	$1.611
concrete	E	23600	39	1	$3,522,633	$90,324	$3.827
concrete	E	24800	59	1	$2,844,012	$48,204	$1.944
concrete	E	25000	57	1	$2,336,464	$40,991	$1.640
concrete	E	41000	40	1	$3,872,232	$96,806	$2.361
concrete	H	129600	39	2	$6,751,173	$173,107	$1.336
concrete	H	151000	39	3	$4,769,856	$122,304	$0.810
concrete	H	153800	56	1	$9,751,000	$174,125	$1.132
concrete	H	182800	44	2	$8,306,276	$188,779	$1.033
Steel	E	62000	49	1	$3,635,453	$74,193	$1.197
Steel	E	63200	60	2	$4,236,686	$70,611	$1.117
Steel	E	65400	47	1	$12,069,038	$256,788	$3.926
Steel	H	195800	46	1	$15,495,850	$336,866	$1.720
Steel	H	199300	43	2	$22,808,071	$530,420	$2.661
Steel	H	200600	55	3	$13,778,325	$250,515	$1.249
Wood	E	34500	51	1	$4,993,519	$97,912	$2.838
Wood	E	38600	45	1	$2,993,957	$66,532	$1.724
Wood	E	38700	51	1	$4,293,190	$84,180	$2.175
Wood	E	41500	56	1	$5,794,040	$103,465	$2.493
Wood	E	46300	51	1	$5,442,593	$106,718	$2.305
Wood	E	46600	55	2	$5,470,567	$99,465	$2.134
Wood	E	47100	44	2	$4,456,160	$101,276	$2.150
Wood	H	282800	55	1	$22,048,276	$400,878	$1.418
Wood	H	294300	51	1	$20,464,940	$401,273	$1.363

6.4.2 Major Repairs Costs' Result

Figure 6.17 presents the probability distribution for major repairs costs of three different conventional structures, which include steel, wood, and concrete. Max Extreme distribution is the best fit for steel alternatives, while the Logistic distribution is the best fit for wood alternatives. The following probability function can be the best fit of the major repairs costs of concrete alternatives: Lognormal distribution.

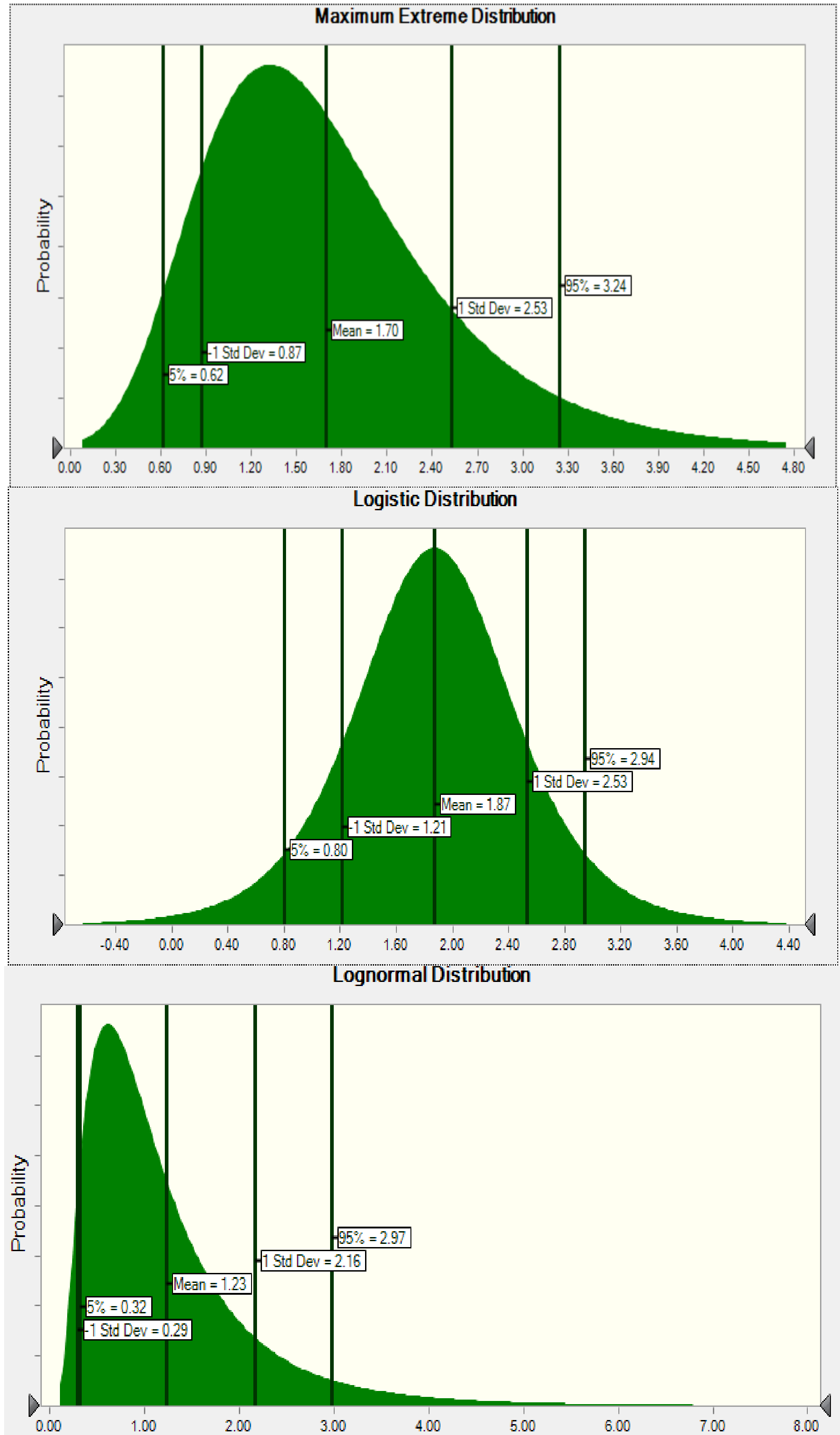


Figure 6.18 Probability distribution functions for major repairs costs of alternatives as displays from up to down; steel, wood, and concrete

Statistical details of major repairs costs that are displayed in Figure 6.33 indicate that the minimum mean value is recorded for conventional concrete alternatives at $1.23 /ft^2, while the maximum mean value is $1.87 /ft^2 for conventional wood alternatives. Steel alternatives have mean value of $1.70.

The minimum MRC at the 95% confidence level is $2.94/ft^2 wood alternatives with no significant difference with concrete alternatives at $2.94/ft^2. At the 70th percentile confidence level, the minimum cumulative is about $1.39/ft^2 for concrete alternatives, followed by steel alternatives at $1.99/ft^2, and then followed by wood alternatives at $2.18/ft^2. Applying of concrete alternatives would reduce the MRC by about 57% and 52% compared to wood alternatives over the 70 percentile confidence level and mean, respectively as shown in Table 6.33.

Table 6.33 Statistical details for major repairs costs for various alternatives

Statistics	**Steel alternatives**	**Wood alternatives**	**Concrete alternatives**
Mean	$1.70	$1.87	$1.23
Median	$1.56	$1.87	$0.97
Mode	$1.32	$1.87	$0.62
Standard Deviation	$0.83	$0.66	$0.94
Variance	$0.69	$0.43	$0.88
Skewness	$1.14	$0.00	$2.74
Kurtosis	5.40	4.20	18.83
Coeff. of Variability	0.488	0.352	0.76
Minimum	∞	∞	∞
Maximum	∞	∞	∞
5% percentile	$0.62	$0.80	$0.32
50% percentile	$1.56	$1.87	$.97
70% percentile	$1.99	$2.18	$1.39
95% percentile	$3.24	$2.94	$2.97

6.5 Operating and Maintenance Costs

The operating and maintenance cost data are gathered from school boards in Montreal. Table 6.34 includes the national average square footage operating and maintenance costs for school buildings in the province of Quebec. These costs include operating costs such as cleaning and energy costs, maintenance costs, and other costs. These costs are not influenced by structure or envelope types. However, they are affected by school level, as presented in table 6.33. The total annual O&M costs for elementary schools is $3.43/ft^2 while the cost for high schools is $2.83/ft^2.

Table 6.34National average O&M costs ($/ft^2) in Quebec's schools (LBPSB, 2011)

School Level	Elementary School	High School
Maintenance	$1.10	$0.90
Cleaning	$1.70	$1.30
Utilities	$0.23	$0.23
Other Costs	$0.40	$0.40
Total	$3.43	$2.83

6.5.1 Maintenance costs

Include labour, plumbers, electricians, locksmiths, mechanical technicians, carpenters, painters, contractors, exterior work, playgrounds, lawn, snow, HVAC, mechanical, plumbing, electrical, structural, architectural, civil works, locks and keys, swimming pools, windows and glass, clocks, intercoms, graffiti removal, uniforms and work clothes (LBPSB, 2011).

6.5.2 Cleaning costs

Cleaning costs include labour, contractors, cleaning equipment, repairs to cleaning equipment, mops, miscellaneous tools, hand-drying paper, toilet paper, wax, cleaning products, garbage bags and containers, carpets, extermination contracts, garbage disposal, uniforms and work clothes (LBPSB 2011).

6.5.3 Other costs

Other costs include management staff at the school board level to oversee the school's building plant, secretarial staff at the school board who help the management staff affected to the building plant, travel expenses, administrative fees, and a truck fleet (gas, insurance, repairs). Other costs also include building security such as central alarm system and security company charges (LBPSB, 2011).

6.6 Environmental Impact Costs (EIC)

6.6.1 Process of EIC Costs Estimating

Environmental impact costs are estimated in this research, and added as future costs to the developed life cycle costs prediction model. Figure 6.18 presents the environmental impact assessment and cost computing process. The environmental impact costs assessment process consists of five main stages: defining a project's general information, defining the school building elements, performing the life cycle assessment, quantifying the environmental impacts in carbon dioxide equivalent (CO_2 e), and finally pricing and calculating the environmental impact costs.

The first stage is where the general information of the tested project, such as type of project (school and its level), area (250,000ft^2), and its life span (20 years) is assembled. This stage includes the significant step of quantifying the electricity and natural gas consumption. This energy consumption is identified based on the results obtained from the energy simulations for elementary and high schools for the various alternatives.

The second step has three major steps: defining the structure, defining the envelope, and defining the interior elements. The quantities and sizes of structural and architectural elements are computed based on the selected prototype model described in the previous chapter. Table 6.35 shows the bill of material for a high school with a wood structure and exterior concrete brick (WC).

The next stage is performing the LCA using ATHENA® software. Seven various structure and exposure systems are assessed over 20 years of operation over all the life cycle stages: manufacturing, transportation, construction, maintenance, operation and end-of-life. In the pre-final stage, Greenhouse gas emissions causing global warming are quantified and then converted to a unified unit equivalent for Carbon Dioxide emissions (CO_2 e).

The current price of environmental impacts is approximately \$30/ ton of CO_2, collected from the carbon market (Pointcarbon, 2011). Environmental impact costs are estimated in the final stage and combined with other life cycle cost elements to compare the economic viability of each alternative.

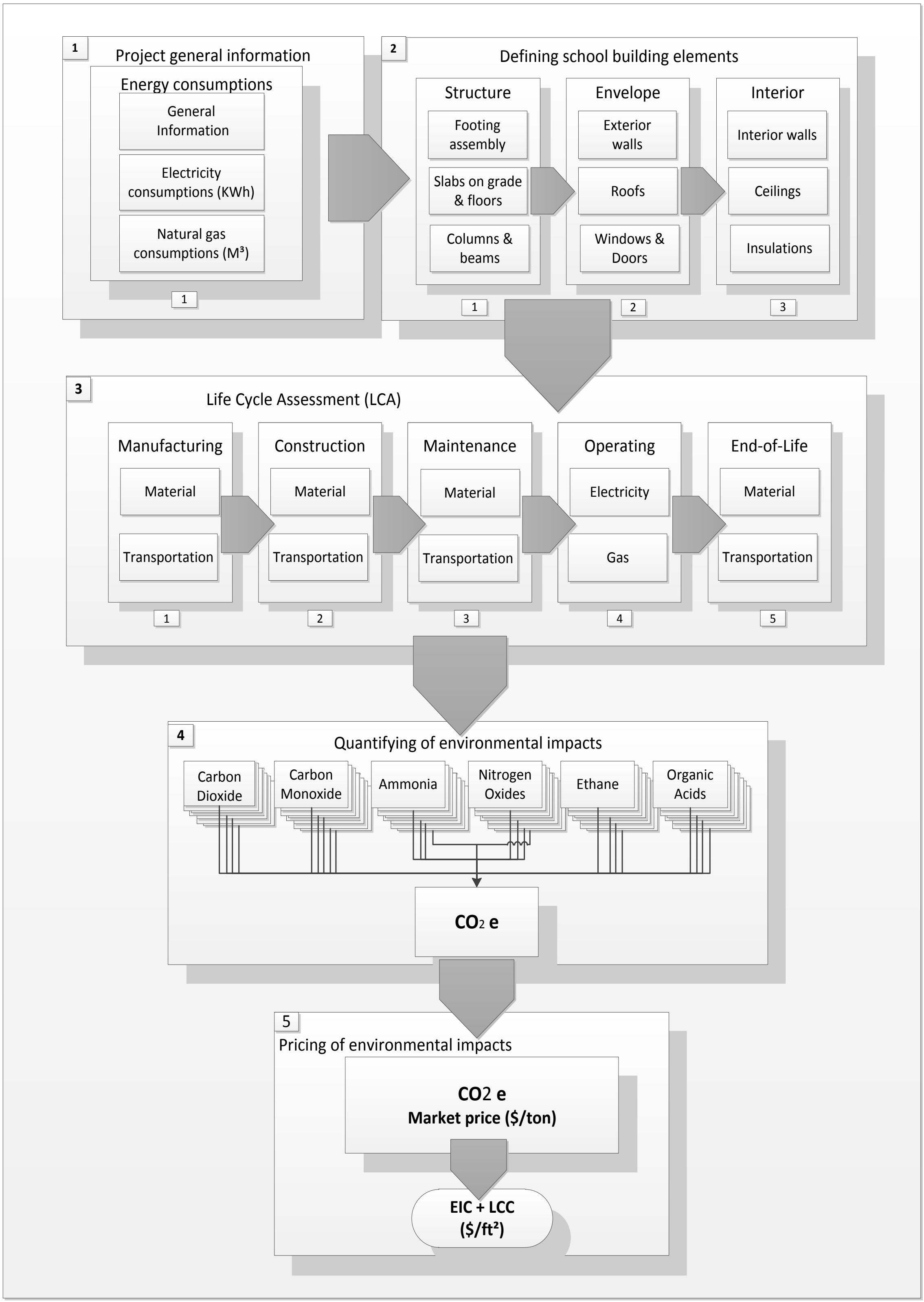


Figure 6.19 Environmental impact costs computing process

Table 6.35 Bill of quantities for a WC alternative conventional high school

Material	Quantity	Unit
3 mil Polyethylene	11845.1381	m2
5/8" Fire-Rated Type X Gypsum Board	25548.3370	m2
Aluminum	0.3084	Tonnes
Batt. Fiberglass	48774.0979	m2 (25mm)
Batt. Rockwool	4877.4098	m2 (25mm)
Cedar Wood Tongue and Groove Siding	2554.8337	m2
Concrete 20 MPa (flyash av)	307.2384	m3
Concrete 30 MPa (flyash av)	1215.5383	m3
Concrete Brick	2438.7049	m2
Foam Polyisocyanurate	97548.1958	m2 (25mm)
Galvanized Sheet	4.2300	Tonnes
Glazing Panel	0.6084	Tonnes
Hollow Structural Steel	27.1450	Tonnes
Laminated Veneer Lumber	635.1644	m3
Large Dimension Softwood Lumber, kiln-dried	745.7211	m3
Low E Tin Glazing	3341.0787	m2
Nails	6.3689	Tonnes
Rebar, Rod, Light Sections	2.2200	Tonnes
Roofing Asphalt	969.0382	kg
Small Dimension Softwood Lumber, kiln-dried	518.5771	m3
Softwood Plywood	74248.2932	m2 (9mm)
Welded Wire Mesh / Ladder Wire	10.4620	Tonnes

6.6.2 Results of Environmental Impacts

The result of the life cycle assessment test indicates that elementary schools have higher global warming impact compared to high schools tested. The reason is that an elementary school has higher natural gas consumption in relation to area, while the high schools recorded higher electricity consumption. This result indicates that natural gas production and consumption contributes more environmental impact than the production and consumption of electricity in the city of Montreal due to the use of hydropower to generate electricity.

A concrete elementary school produces the lowest overall global warming potential impact, while steel buildings contribute the highest, among the other systems studied. Concrete school buildings produce about 76.32 and 66.40 (Kg CO_2e/ft^2) for elementary and high schools, respectively, while steel buildings generate 90.62 and 76.22 (Kg CO_2e/ft^2), as presented in Table 6.36.

Table 6.36 Total quantified environmental impact for tested school buildings

School level	Elementary school (75,000ft^2)		High school (250,000ft^2)	
Alternative	EI (Kg CO_2e/ft^2)	EI (ton CO_2e)	EI (Kg CO_2e/ft^2)	EI (ton CO_2e)
(WW)	85.47	6,410	72.40	18,100
(WC)	83.20	6,240	69.76	17,440
(SS)	90.62	6,797	76.22	19,056
(SC)	89.12	6,684	74.78	18,696
(SW)	84.53	6,340	71.25	17,812
(CM)	86.40	6,480	76.16	19,040
(CC)	76.32	5,724	66.40	16,600

6.6.1.1 Global Warming Potential of Elementary Schools

Concrete elementary school buildings produce about 5,724 tons of CO_2 e, masonry 6,480,wood with brick 6,240,, wood 6,410,, steel with brick 6,684, steel with wood 6,340, and steel 6,797 tons of CO_2 e over a 20-year life span, as can be seen in Figure 6.19.

6.6.1.2 Global Warming Potential of High Schools

Concrete high school buildings produce about 16,600 tons of CO_2e, masonry 19,040 , wood with brick 17,440, wood 18,100, steel with brick 18,696, steel with wood 17,812, and steel 19,056 tons of CO_2 e over a 20-year life span, as can be seen in Figure 6.20.

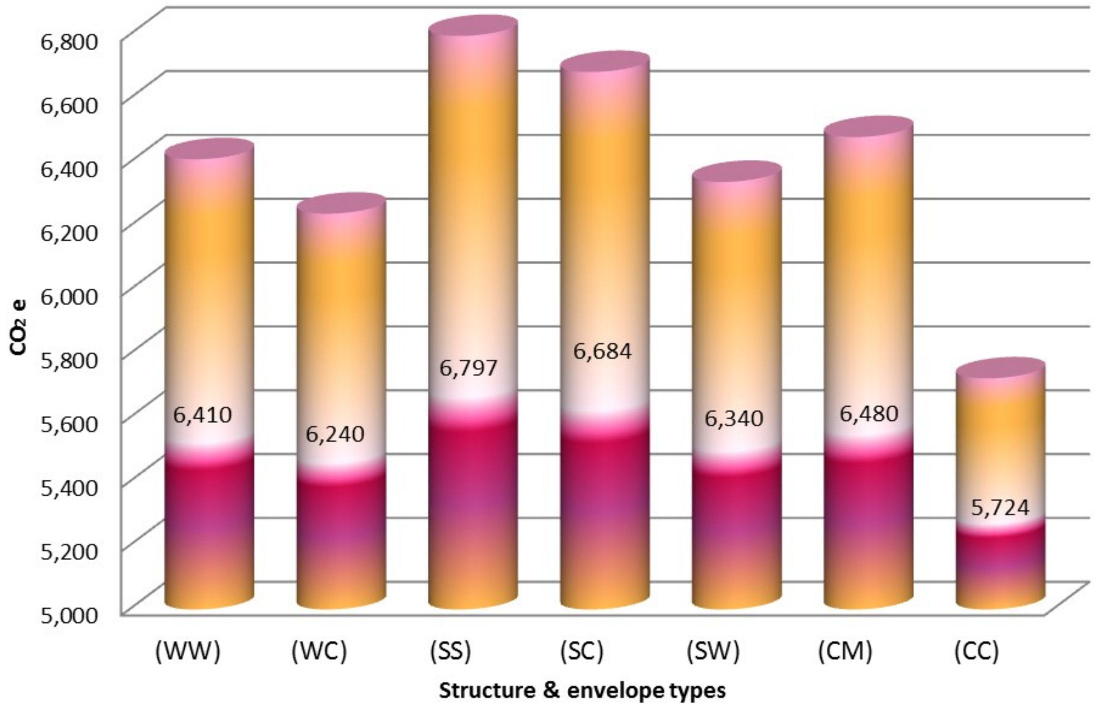


Figure 6.20 Total quantified environmental impacts for tested elementary schools

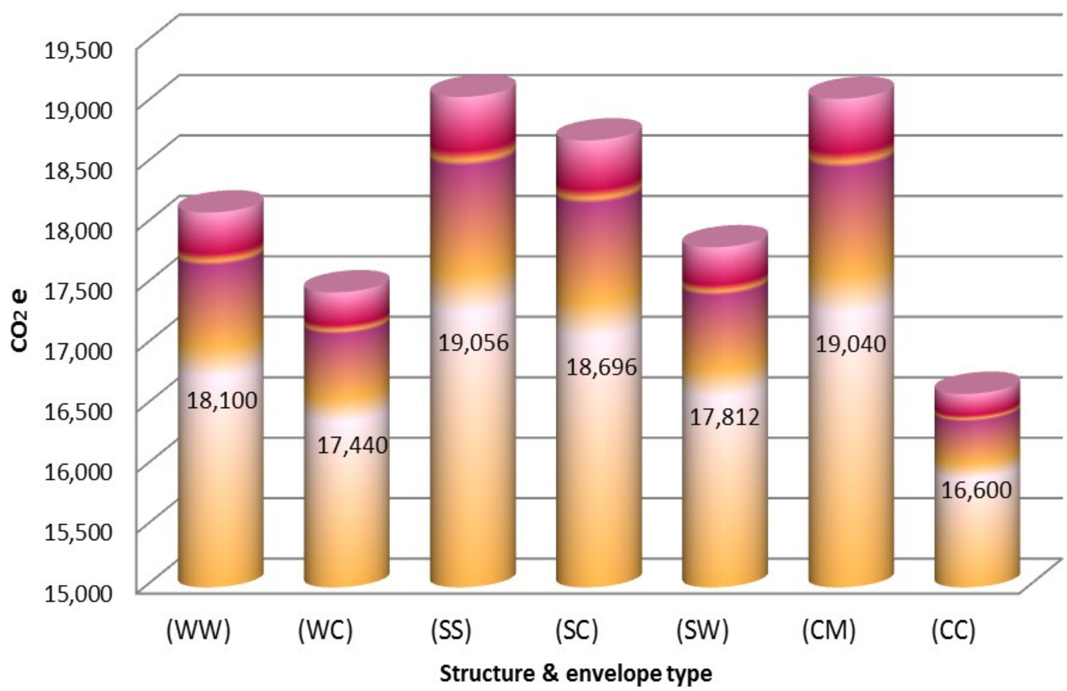


Figure 6.21 Total quantified environmental impacts for tested high schools

6.6.2 Environmental Impact Cost Results

Table 6.36 presents the square footage and total environmental impact costs for elementary and high school buildings after 20 years of operation

6.6.2.1 Elementary School EICs

The Environmental impact cost (EIC) results for a 75,000 ft^2 elementary school building show that the minimum environmental impact cost is recorded at $171,700 for a concrete building (CC), while the maximum value is observed to be $203,900 for a steel building (SS), as shown in Table 6.37.

Table 6.37 Total environmental impact costs for tested school buildings

School level	**Elementary school (75,000ft²)**		**High school (250,000ft²)**	
Alternative	EIC ($/ft²)	EIC ($)	EIC ($/ft²)	EIC ($)
(WW)	$2.56	$192,300	$2.17	$543,000
(WC)	$2.50	$187,200	$2.09	$523,200
(SS)	$2.72	$203,900	$2.29	$571,700
(SC)	$2.67	$200,500	$2.24	$560,900
(SW)	$2.54	$190,200	$2.14	$534,400
(CM)	$2.59	$194,400	$2.28	$571,200
(CC)	$2.29	$171,700	$1.99	$498,000

EIC is recorded at $192,300 for wood buildings (WW), $187,200 for wood with brick (WC), $200,500 for steel with brick (SC), $190,200 for steel with wood (SW), and $194,400 for masonry buildings (CM), as shown in Figure 6.21.

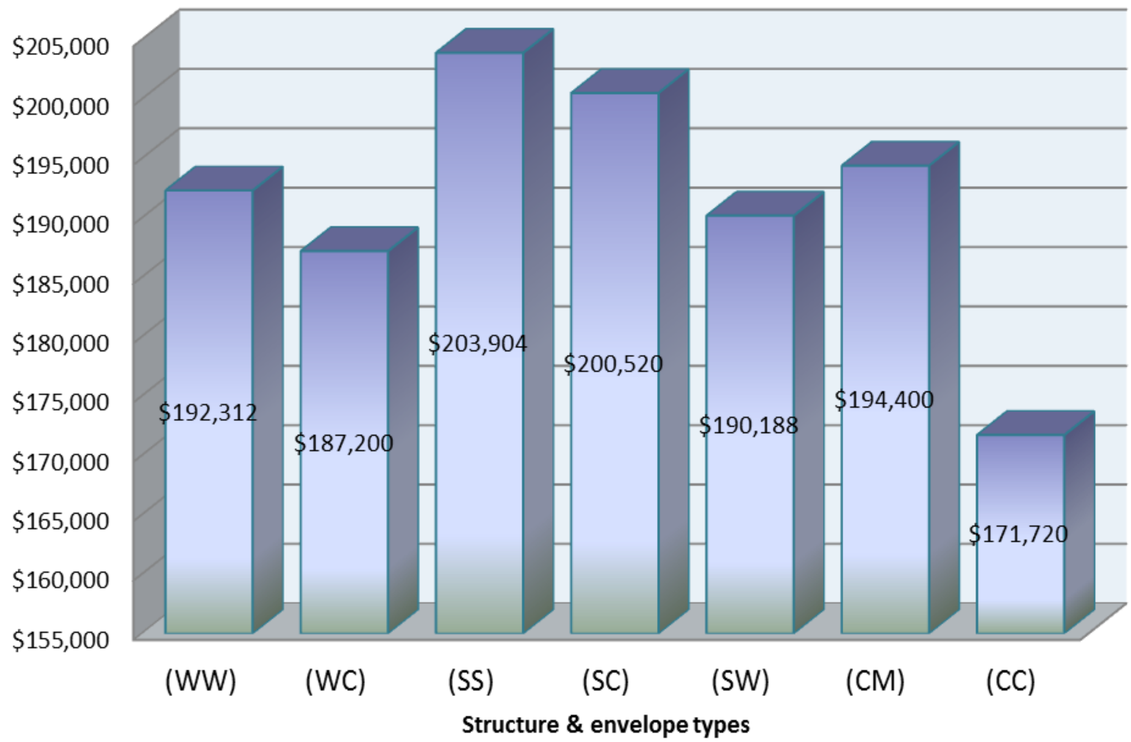


Figure 6.22 Total environmental impact costs for elementary school buildings

6.6.2.2 High School EICs

Environmental impact cost results for a 250,000 ft^2 high school building show that the minimum environmental impact cost is recorded at $498,000 for a concrete building (CC), while the maximum value is observed at $571,700 for a steel building (SS). The EIC is recorded at $543,000 for wood buildings (WW), $523,200 for wood with brick (WC), $560,900 for steel with brick (SC), $534,400 for steel with wood (SW), and $571,200 for masonry buildings (CM), as shown in Figure 6.22.

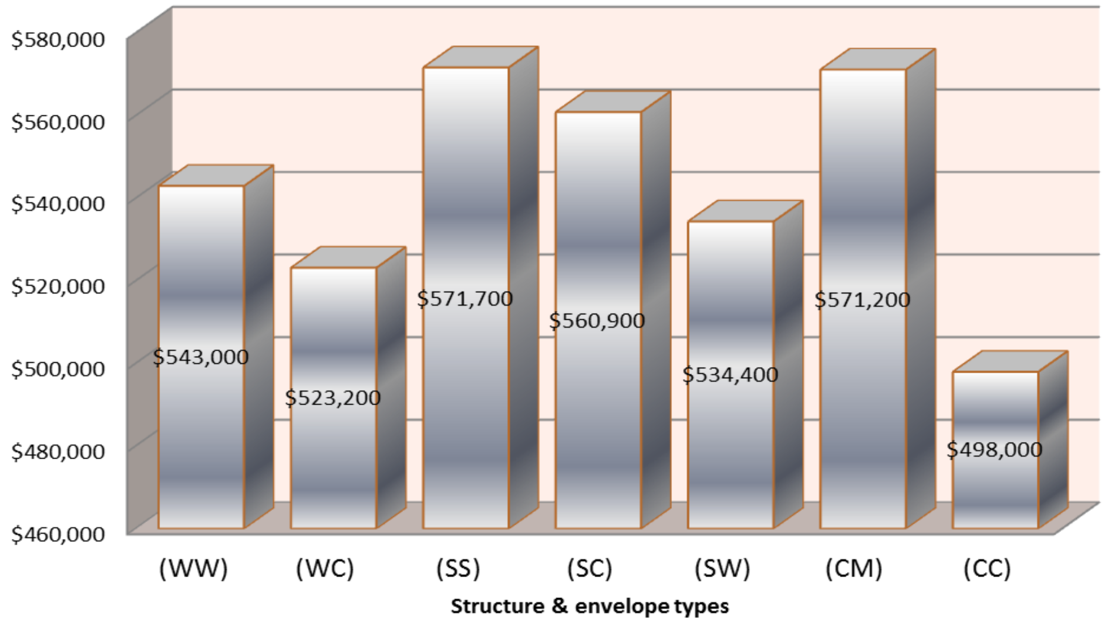


Figure 6.23 Total environmental impact costs for high school buildings

6.7 Salvage Value of School Buildings

Salvage value is computed in this study using the assumption of a straight line depreciation method, which is commonly used in the depreciation of commercial buildings (ASLLC, 2011). This method depends essentially on the expected functional (useful) life of a school building. The National Center for Educational Statistics conducted a study measuring the functional age of 900 school buildings in the United States. Most of the schools investigated by the NCES had a functional age of 5-34 years, while 14% had a functional age of 35 years or more (NCES, 2000). In this study, the functional or useful life of various structure and envelope types is excerpted from the Means Facilities Maintenance Standards. Table 6.37 presents the average useful life, percentage of annual depreciation, and the expected salvage value after 20 years.

The expected average life of a school building is found to be influenced essentially by both structure and envelope types (RS Means, 2009). The average useful life in this study varies between 20-50 years, as shown in table 6.38. The minimum expected average life is 20 years for pure wood buildings while the maximum is 50 years for precast concrete buildings. Twenty-five is the average life expected for wood with exterior brick, 30 years for pure steel buildings and steel with wood stud walls, 35 years for steel with exterior brick, and 45 years for masonry buildings with cavity walls. The annual depreciation is computed for each alternative using the straight line method by dividing the number of years over the total expected life. Total depreciation is calculated after 20 years of school operation in order to estimate the salvage value. Salvage value in this study is equal to the book value, which is the remaining monetary value of a project after depreciation. Salvage value is computed as a percent of the initial cost of a school building, which varies from 0.0% to 60% depending on structure and envelope type.

Table 6.38 Expected useful lives, depreciation, and salvage values for different structure and envelope type (RS. Means, 2009)

Alternative	Functional age (years)	Annual depreciation	Depreciation after 20 years	Salvage value after 20 years
(WW)	20	5.00%	100%	00.0%
(WC)	25	4.00%	80.0%	20.0%
(SS)	30	3.33%	66.6%	33.3%
(SC)	35	2.85%	57.0%	43.0%
(SW)	30	3.33%	66.6%	33.3%
(CM)	45	2.22%	45.6%	54.4%
(CC)	50	2.00%	40.0%	60.0%

6.8 Sustainable School Buildings

Sustainable school buildings are investigated in this study and compared to conventional ones. Data from 142 LEED certified schools in the United States and Canada is collected and classified into seven groups based on their structure and envelope types. A list of LEED certified schools is gathered from the US Green Buildings Council and contains some limited data such as school name, location (city and state), level of certification, score obtained, year of construction, and the area of each school. Although these are significant data, other vital data is collected or assumed (in accordance with conventional schools).

6.8.1 Initial Costs (LEED certified buildings)

The initial costs of LEED certified school buildings are gathered from many different resources, such as articles, green building council websites, school board websites, and other green building's websites. The initial costs of 142 LEED certified school buildings, located in 115 various cities in North America, are determined. Each of these locations is adjusted to reflect being in the city of Montreal in order to measure the economic performances of every alternative and to compare them. Furthermore, these buildings are built at times which requires time adjustments to each so that they can be used for future predictions and comparisons. Table 6.39 presents the time and city adjustment index factors for sustainable school buildings.

Green school buildings have cost premiums that are added to the initial costs to achieve their high performance levels by reducing their initial environmental imprint and their consumption of energy, water, and other resources. These cost increases vary from one project to another depending on type and quantity of treatments as well as in regards to other considerations such as location and year of construction. The focus of this study is to measure the effect of structure and envelope types on green school costs.

Table 6.39 Time and location adjustment factors for LEED® certified schools

City	State	adjusted city	city factor	time	time factor	adjusted time and location
Diablo Lake	WA	1.063	0.96	2000	1.529	1.625
Dalles	OR	0.981	1.04	2000	1.529	1.500
Hanover	PA	1.097	0.93	2001	1.479	1.622
Grand Rapids	MI	1.200	0.85	2001	1.479	1.775
Baltimore	MD	1.121	0.91	2001	1.479	1.658
Bolingbrook	IL	0.936	1.09	2002	1.437	1.345
College Park	GA	1.133	0.9	2002	1.437	1.628
N Charleston	SC	1.360	0.75	2002	1.437	1.954
San Jose	CA	0.857	1.19	2003	1.401	1.200
Alexandria	VA	1.121	0.91	2003	1.401	1.570
Birmingham	AL	1.172	0.87	2003	1.401	1.642
Fort Collins	CO	1.097	0.93	2003	1.401	1.536
Prewitt	NM	1.146	0.89	2003	1.401	1.605
Virginia Beach	VA	1.214	0.84	2004	1.287	1.563
Hampton Bays	NY	0.816	1.25	2004	1.287	1.050
Corvallis	OR	0.981	1.04	2004	1.287	1.262
Phillipsburg	NJ	0.936	1.09	2004	1.287	1.204
Washington, D.C.	DC	1.074	0.95	2004	1.287	1.382

6.8.2 Energy Costs of LEED Certified Buildings

Energy consumption of LEED certified school buildings is investigated separately since they are located in various climate zones, and since the data is not available in one resource. The energy consumption of green school buildings is mostly lower than the energy consumption of conventional school buildings. The reduction in energy consumption is always compared to the ASHRAE 90.1 baselines. These baselines were developed to meet the minimum code requirements of ASHRAE 90.1, 2004. They are the result of school building energy simulations performed by Energy Design Guide for K-12 Schools in each of the climate zones in North America. Figure 6.23 shows the baseline of energy consumption across North American climate zones.

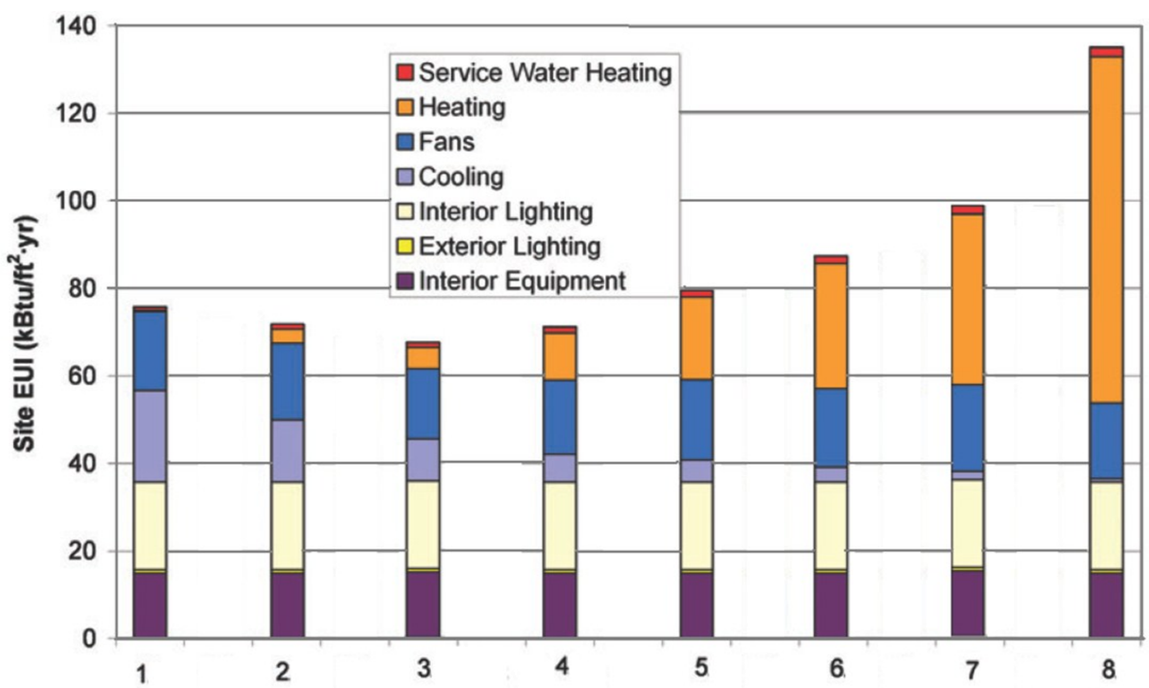


Figure 6.24 Energy consumption baseline across NA climate zones (ADEG, 2008)

This study is performed on school buildings in the City of Montreal, in climate zone 6, and so the energy baseline consumption is computed for electricity and natural gas. The total energy consumption of baseline at climate zone 6 is found to be approximately 83.0 kBtu/ft^2 for high schools and 85.0 kBtu/ft^2 for elementary schools. Gas consumption is found to be one-third of electricity consumption for both school levels. Total energy costs for the baseline in climate zone 6 is about \$1.98/ft^2 for high schools and \$2.03/ft^2 for elementary schools, as presented in table 6.40.

Table 6.40 Baseline energy consumption and costs for climate zone 6 (ASHRAE, 2004)

School Level	Energy (kBtu/ft^2)	Gas (m^3/ft^2)	Electricity (Kwh/ft^2)	Gas cost (\$/ft^2)	Electricity cost(\$/ft^2)	Energy cost (\$/ft^2)
Elementary	85	0.743	16.99	\$0.393	\$1.63	\$2.03
High	83	0.715	16.70	\$0.379	\$1.60	\$1.98

The square footage energy cost for each green school is computed based on the annual energy costs computed for the ASHRAE baseline in climate zone 6.

6.8.3 Operating and Maintenance Costs (LEED certified buildings)

O&M costs include cleaning costs, utilities such as water, and maintenance costs. Cleaning cost is found to not be influenced by applying various structure and envelope types nor by applying sustainability principles (Bruno, 2011).

6.8.3.1 Water Consumption Costs

Water efficiency is one of the significant categories considered by the LEED rating system. Each LEED certified school building has reduced their water use by a certain percentage compared to conventional schools. An annual maintenance and operations cost study for American schools shows that the square footage water consumption cost for a conventional school building is approximately \$0.22/ft^2/year (Agron, 2008). This value is adjusted to year 2011 in the city of Montreal as being \$0.23/ft^2/year. The water reduction achieved by each green school is multiplied by the computed value and then subtracted from O&M costs accordingly.

6.8.3.2 Maintenance Costs

Studies in green building performance show that they realize a substantial average saving in maintenance costs of 13% compared to conventional buildings (Studio4, LLC, 2009). A feasibility study conducted on office buildings indicated that the reduction of maintenance costs is affected by the level of LEED certification, with a 3% variance of reduction associated to each subsequent level (Alkass, 2008).

The assumption of O&M cost reduction is developed according to the above-mentioned studies with regards of the level of certification. A 13% reduction in maintenance costs is assigned to the platinum certified schools, 10% is for gold certified schools, 7% for silver, and 4% for bronze-certified schools, as presented in table 6.41.

Table 6.41 Maintenance cost reduction of sustainable school buildings

LEED scores	LEED certification level	Maintenance cost reduction
26-32	Certified (bronze)	4%
33-38	Silver	7%
39-52	Gold	10%
53-69	Platinum	13%

6.8.4 Major Repairs Costs (LEED-certified buildings)

The MR cost for sustainable school buildings is assumed to be influenced by the certification level with regards to structure type. For example, the reduction in maintenance costs of green concrete buildings that achieved gold certification is 10% less than what could be achieved with a conventional concrete building.

6.8.5 Environmental Impact Costs (LEED-certified buildings)

The environmental impact or carbon dioxide emissions are found to be influenced mainly by the operating energy consumption. The sustainability assessment model proved that 90% of the total CO_2 emissions are caused by the operating energy consumption. Studies in green building performance show that substantial average savings in maintenance costs of approximately 13% are possible (Studio4, LLC, 2009). The average carbon dioxide emission reduction in green buildings is about 33% lower than for conventional buildings (Studio4, LLC, 2009). Two LEED-certified buildings show that CO_2 emission is correlated to energy consumption with margin of ± 5.0%, as shown in Table 6.42. The averages of CO_2 emissions and energy reductions in both buildings are 37.5%.

Table 6.42 Energy and environmental impact reduction in sustainable schools

LEED certified school	**Energy Reduction**	**CO_2 emissions reduction**
Greybull elementary	35 %	40 %
G.D. Rogers Garden elementary	40 %	35 %

To sum up, the assumption of environmental impact vs. the energy consumption for sustainable school buildings with regards to structure and envelope type is:

(%) Energy reduction = (%) CO_2 emissions reduction.

6.8.6 Salvage Value (LEED-certified buildings)

The assumption of salvage value for a sustainable school is similar to the assumption for a conventional school. The salvage value is estimated using straight line depreciation which is affected by structure and envelope type as well as by the expected functional age.

6.9 Development of LCC Forecasting Models

The development of Life cycle forecasting model for conventional and sustainable school buildings consisted of several major stages, as shown in Figure 6.24. These stages include defining school parameters, defining the alternatives, measuring life cycle costing components, and system modeling using stochastic and deterministic approaches.

6.9.1 Defining School Parameters

The first stage of developing an LCC forecasting model is defining school parameters such as structure and exposure type, school area, number of floors, school level, sustainability level, location (city), and year of construction. Each of these parameters has an impact on some of the LCC components which consequently influence the overall LCC.

6.9.2 Defining of the alternatives

All of the possible alternatives are identified at this stage to be measured and compared in order to select the most favourable alternatives. Fourteen various alternatives representing the two main groups of school buildings, conventional schools and sustainable, are selected. Each group consists of seven alternatives for structure and envelope types.

6.9.3 Computing of Life Cycle Costing Components

LCC components such as initial costs, operating costs, environmental impact costs, and salvage values are evaluated separately and given specific weights based on their importance. All of these components are estimated using various methods.

6.9.3.1 Conventional School Buildings

Initial costs are calculated using RS Means with regards to certain significant parameters such as structure and exposure types, school area, number of floors and school level. Regression models are developed based on structure and envelope types to compute the initial costs for conventional school buildings.

Operating costs contain three components: energy costs, operating and maintenance costs, and major repair costs. Energy costs are calculated for electricity and natural gas consumption using an energy simulation method with regards to the type of exposure and school level. Operating and maintenance cost data are gathered from school boards in Montreal to estimate cleaning costs, utilities, and maintenance costs relative to school level. Major repair data are gathered for 400 school buildings from 140 cities in North America with regards to structure and envelope types and school levels.

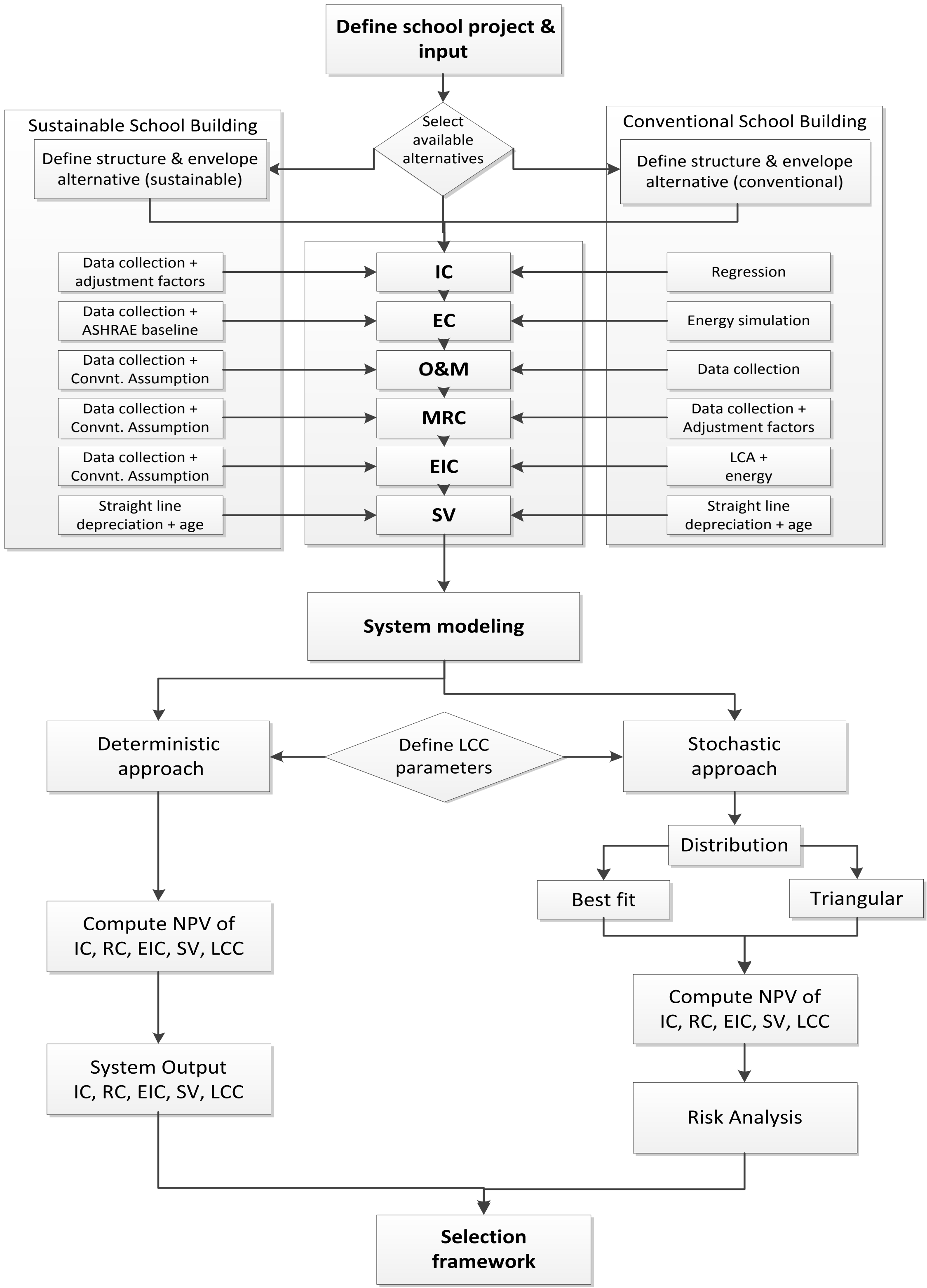


Figure 6.25 Development of LCC forecasting models using various approaches

Future costs such as environmental impact costs are calculated using the energy consumption and life cycle assessment tool, in accordance with structure and envelope types and school level.

Finally, salvage values are computed using the straight line method with regards to structure and exposure types and the average expected useful life.

6.9.3.2 Sustainable School Building

The initial costs of sustainable school buildings are gathered for 142 LEED-certified school buildings in about 120 cities in North America. This data is organized according to the schools' structure and exposure type, and adjusted for the city of Montreal at year 2011.

Operating costs such as energy costs are computed according to the energy consumption reduction compared to the ASHRAE baseline of that climate zone. Operating and maintenance costs and major repair costs are assumed to be 13% less than the costs of conventional schools and are influenced by the level of sustainability achieved.

Environmental impact cost reduction is assumed to be correlated to the reduction of energy costs with regards to structure and exposure types. Salvage values are computed using the straight line depreciation method in relation to the average useful life.

6.9.4 System Modeling

System modeling is performed by developing cash flows based on computing LCC components for the whole range of alternatives. LCC modeling is performed in this study using two approaches: stochastic and deterministic. Since life cycle cost parameters usually are uncertain, the net present value of each LCC component is computed, mainly using the stochastic method, which is performed utilizing the probability distribution function. The deterministic approach is applied since school boards (end users) may not be interested in considering the uncertainties.

6.9.4.1 Deterministic Approach

In this approach, the LCC component is assumed to have point value or deterministic cost. For example, initial costs, energy costs and environmental impact costs are estimated mainly using the deterministic approach. The other costs such as operating and maintenance costs, major repairs costs, and salvage values are computed using the average deterministic values. The net present value of the overall LCC and LCC components are estimated using the following equation:

$$\boldsymbol{LCC}\ (\boldsymbol{NPV}) = -IC - \left((EC + O\&M + MRC) * \left(\frac{1-\left(((1+j)^{n}) * ((1+i)^{-n})\right)}{i-j}\right)\right) - \left(EIC * ((1+i)^{-n})\right) + \left(SV * ((1+i)^{-n})\right)$$

(Equation 6.10)

where:

IC = Initial Costs

RC = Running Costs which include $(EC + O\&M + MRC)$

EC = Energy Costs

$O\&M$ = Operating & Maintenance costs

MRC = Major repairs costs

SV = Salvage value

EIC = Environmental Impact costs

i = Discount Rate

j = Inflation Rate

n = study period

Other LCC components such as study period, discount rate and inflation rate are identified deterministically. The study period is assumed to be 20 years, which represents the shortest time horizon (life span) of one of the alternatives. The discount rate is estimated to be 5.0% and the inflation rate 2.0% as gathered from the Bank of Canada. The net present values for each LCC parameter are forecasted to start at year 2011 and end at year 2031in the City of Montreal. After calculating the NPV for the alternatives of each LCC component, comparison of the alternatives and then the selections are performed by applying the developed selection framework.

6.9.4.2 Stochastic Approach

A stochastic model is developed using a probabilistic approach that utilizes a probability distribution function for all of the uncertain parameters and therefore addresses and deals with the uncertainty in the model.

The first step of this model is identifying the variable or the uncertain parameters. These parameters include the overall computed LCC or the collected components, as well as other general LCC parameters such as discount and inflation rates. The period of study is set at 20 years.

The next step is defining the probability distribution for each predefined and uncertain parameter that covers all possible values of each parameter.

The probability distributions are defined via various functions according to the data collected and the computed cost values. Figure 6.25 shows the calculation equation of Net Present Value (NPV) for LCC and its components using various probability distributions, in which

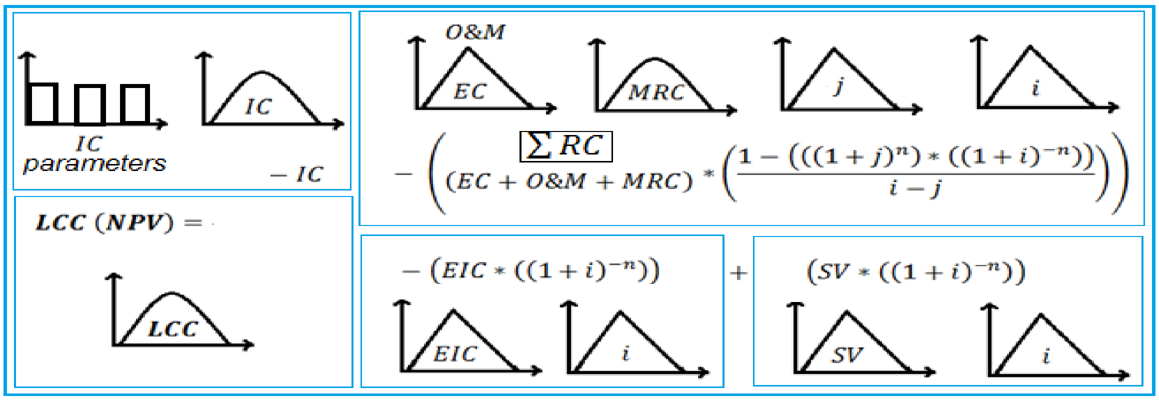


Figure 6.26 Calculating NPV using Monte Carlo simulation

NPV, the probability distribution of the net present value for LCC and its components, is calculated for each alternative using initial cost parameters such as number of floors, school area and school level, expressed by discrete distribution functions to addreess uncertainities associated with the developed regression models. Cost componet data such as EC, O&M, EIC, and SV are expressed by trinagular probaibility distribution, as they have determinestic values. Major repairs collected cost data are established using the best fit distibution functions due to the large amount of gathered data. (i, j) rates are expressed using tringular probability distribution as they were gathered from the Bank of Canada.

In the next step, Monte Carlo simulation is applied using Oracle Crystal Ball 2011 software to create a probability distribution function for the life cycle cost components (e.g. NPV). The Monte carlo simulation is performed initially by the generation of random numbers from 0.0 – 1.0 . Random numbers are then used to enter the predefined cumulative probability distribution to get the random values for the uncertain variables. This process is repeated thousands of times to generate the probability distribution function that is built from the random numbers.

The Monte Carlo simulation technique results in various probability distributions for the NPV, from which one can obtain meaningful estimates of the 95th precentile (95-percent confiedence level), median (50-percent confiedence level), and other relevant quantitties. Risk analysis is applied to enable decision makeres in school boards to select structure alternatives based on their acceptable level of risk. The final decision is made via the developed selection framework.

6.10 Selection Framework Development

The Selction Framework is developed using the Analytical Hierarchy Process (AHP) and the Multi Atribute Utility Theory (MAUT). These techniques are applied on the experts' opinions gathered through the distribution of surveys to school boards. Figure 6.26 presents the developmnet process of the selection framework.

The first step in developing this framework is measuring the performance of each alternative on each selection criterion. These measurements include the outputs of the LCC forcasting model, the sustainability assessment model, and the computed LEED scores for existing sustainable school buildings.

Selection criteria such as initial costs, running costs, environmental impact costs, salvage values and sustainability are evaluated and given relative weights by experts by means of pairwise comparison and AHP techniques.

Utilitiy curves for the selection criteria are developed in the next step using the judjment of experts based on the measured performances of the variouse alternatives. In this step, the various measurement scales are converted to a unified scale (utility score).

The measured performance of each alternative in each criterion is plotted in the developed utililty curve and the utiltiy score is computed accordingly. The obtained utility score is multiplied by that criterion’s weight and the score is estimated. This process is repeated for all alternatives and criteria.

The total scores are computed for each alternative and compared. The final selection is made based on the highest total obtained score. Total score values are calculated using the developed framework which can be illustrated by the following mathematical model:

$$Vi\,(X) = \sum Wi\;Ui =$$

$$(W_{IC}\,U_{IC}) + (W_{RC}\,U_{RC}) + (W_{EIC}\,U_{EIC}) + (W_{SV}\,U_{SV}) + (W_{SUS}\,U_{SUS})$$

(equation 6.12)

Where:

$Vi\,(X)$ = Total Score Value

W_i = weight of criteria

U_i = Utility score

W_{IC} = Importance weight of initial costs

U_{IC} = Utility score of initial costs

W_{RC} = Importance weight of running costs

U_{RC} = Utility score of running costs

W_{EIC} = Importance weight of environmental impact costs

U_{EIC} = Utility score of environmental impact costs

W_{SV} = Importance weight of salvage values

U_{SV} = Utility score of salvage values

W_{SUS} = Importance weight of sustainability

U_{SUS} = Utility score of sustainability

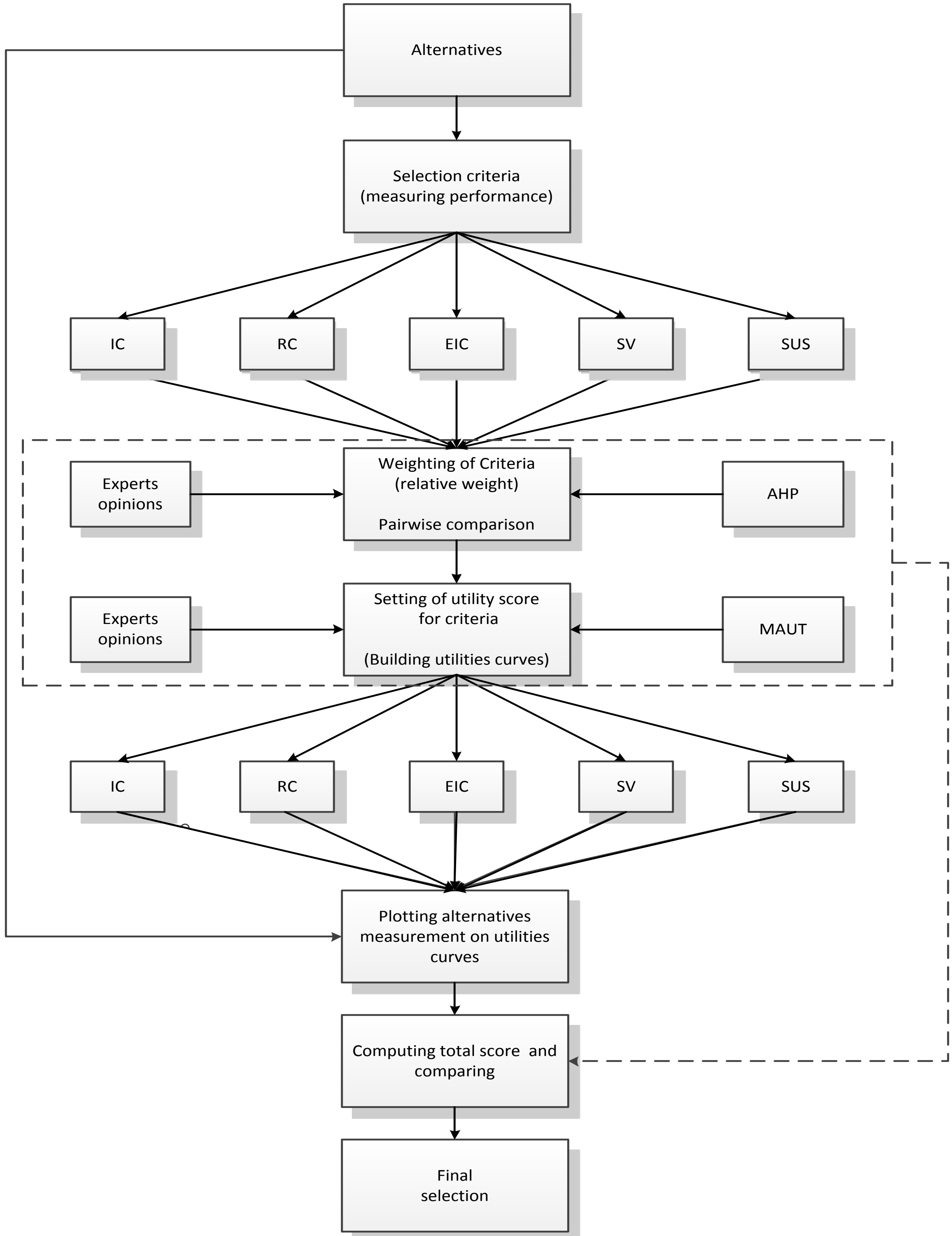


Figure 6.27 Selection framework development process

6.10.1 Integrated LCC and sustainability Models with Selection Framework

Figure 6.27 shows the integrated selection process that starts by identifying school parameters and results in the selection of the most attractive structure and exposure system based on selection criteria of LCC and sustainability.

The user is asked first to identify the school parameters such as school area, school level, and number of floors. The other general parameters such as city, time of prediction, study period, utilities rates, inflation and discount rates are predefined and can be changed if required. The user is then asked to select the alternatives to be investigated and whether to consider sustainability or not. If yes, he/she should select the possible sustainable alternatives.

In the next stage, the user is asked to set weights for the selection criteria if required. The default weights are already assigned based on experts' opinions. In addition, the user is asked to set utility scores for each criterion and to develop utility curves for the various selection criteria. The default utilities curves are made according to the experts' opinions. Any modification in the general parameters causes a change in the default or the built utility curves, which then require resetting of the utilities curves by the user.

At the next stage the user is asked if he/she is willing to apply uncertainty. If the answer is negative, the default calculation is performed applying the deterministic approach. The net present values are estimated for all the LCC components for every alternative. The results of this simulation are presented for each alternative in detail, for every LCC component such as initial costs, energy costs, operating and maintenance costs, major repairs costs, environmental impact costs, and salvage values. The outputs are presented in different ways: detailed cost in $/ft^2$, total cost in$, LCC in NPV $/ft^2$, and total LCC in NPV $. The results are plotted on the utility curves and the utility scores are estimated accordingly. The total score is estimated by adding up the results of multiplying utility scores by criteria weights. The alternatives are compared and a decision is made (final selection) accordingly.

If the user is willing to apply uncertainty, the stochastic approach is applied. This method requires two main issues to be resolved, selecting the distribution and defining the required confidence level. The default distributions are selected based on the best fit to the available data. This process will require users to utilize the crystal ball software to select the distribution and perform the simulation, applying the Monte Carlo technique. The user is then asked to transfer the output data to the developed modeled software. Once the level of confidence is determined, the user is asked to run the stochastic system. The results for each alternative are presented in a range of net present values for each cost component's and LEED scores in sustainability criteria. These results are plotted in the utilities function graphs in order to compute the final utility score. The result of this approach is presented in a range of utilities scores which decision makers can use to base their decision(s) upon.

Finally, the user has the option to perform risk analysis based on his/her experience and to compare the alternatives. The final step is the selection of the best structure and envelope type based on LCC and sustainability criteria.

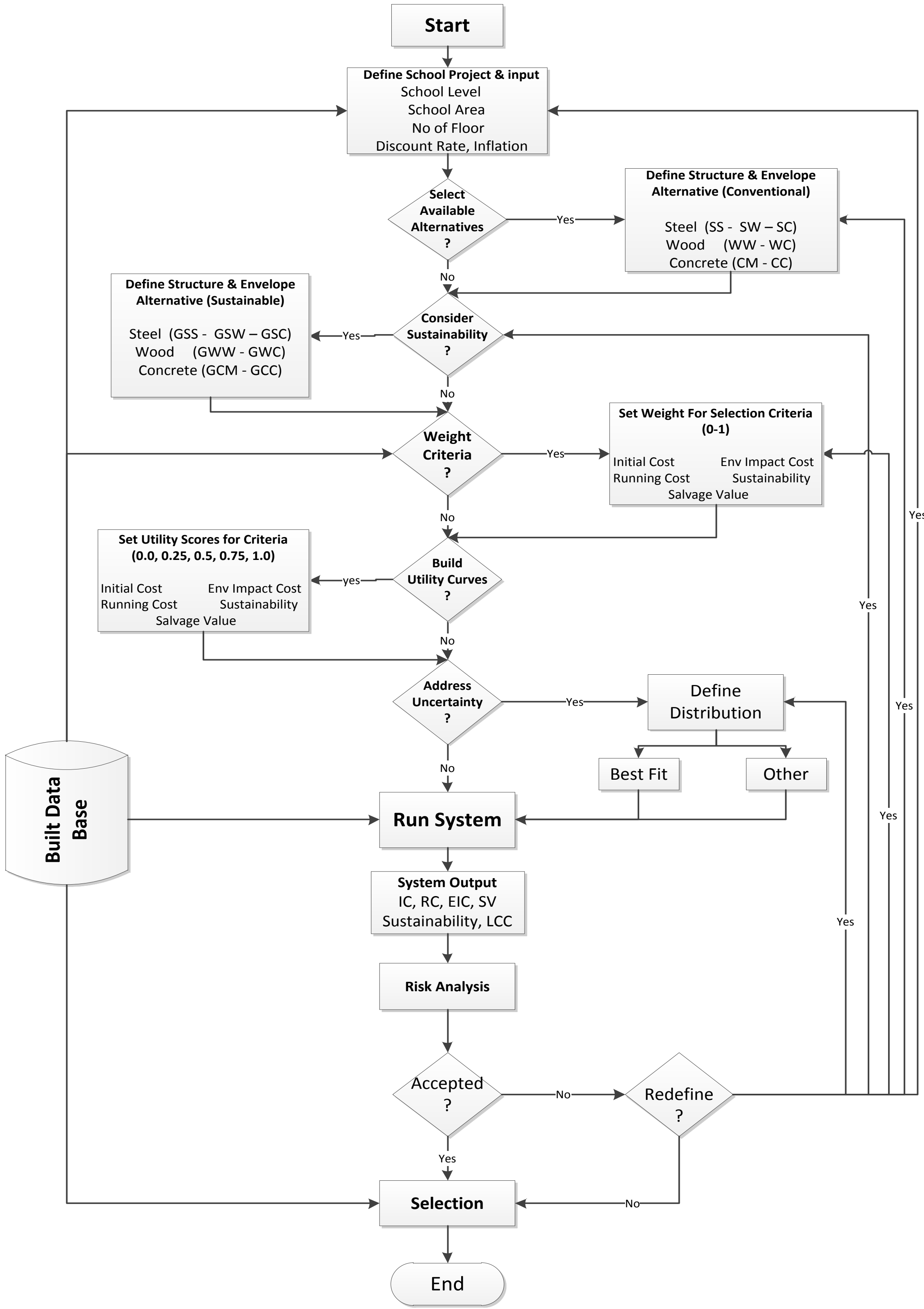


Figure 6.28 Integrated process of the LCC forecasting models and selection framework

6.10.2 Selection Framework Survey

A selection framework is developed in this thesis based on developing LCC forecasting models as well as collecting data from experts in school boards and ministry of education in Quebec via questionnaires. The survey has two main objectives. The first objective is to collect decision makers' opinions to determine the relative weights for the various selection criteria that could govern the selection of structure and envelope types for new school buildings. These weights are determined using the Analytical Hierarchy Process (AHP), applied with the Eigen-vector technique. The second objective of the survey is to determine the preference utility values for the different criteria by applying the Multi Attributes Utility Theory (MAUT) approach. The basic principal of MAUT is the use of utility functions that transform different criteria with various dimensions to a dimensionless scale that can range from 0 to 1 or 1 to 10 or 0 to 100.

6.10.2.1 Preliminary Survey (Pilot Study)

A pilot study is conducted by designing a hard copy survey which was then sent to seven school boards in Montreal. This preliminary study is a significant tool to improve the quality and efficiency of the questionnaire prior to conducting a much larger survey. Only one expert participated in this study. Vital modifications were performed to accommodate his comments. The response to the feedback included the following modifications: providing the background of the research, explaining some questions with examples, translating the questionnaire into French, and distributing electronic pre-formatted surveys.

6.10.2.2 Main Survey (Large Study)

A web-based survey was developed according to the pilot study feedback and distributed to about 250 school boards in Canada. This study was conducted in eight different provinces and distributed in both English and French. Building managers in the Ministry of Educations in Quebec, directors of materials and resources departments, as well as facilities management supervisors were targeted in this study. Only 27 responses were received: five from Quebec, seven from Alberta, one from Nova Scotia, one from Saskatchewan, two from Manitoba, one from Newfoundland, five from Ontario and five from British Colombia. The responses were collected mainly from experts through emails sent by the web-based system. The questionnaires were then perused many times and discussed with certain experts.

6.10.3 Evaluation and Weighting of Selection Criteria Using the AHP

The selection criteria are weighted by the decision makers and experts in school boards using pair-wise comparison matrix and the AHP. The experts are asked first to fill out the matrix using the AHP decision making method. This method helps to quantify the relative weights for a given set of criteria with regards to a priorities scale ratio from 1 to 9. The relative weights are calculated based on the pair-wise matrix and the scales provided by experts. A sample of the calculation matrix is presented for one expert in Table 6.43. The sample consists of two main tables. The upper table represents the pair-wise comparison matrix of the selection criteria, and the lower table consists of several significant columns, as follows:

Column (A) shows the calculation of the geometric mean for the values in the rows in the pair-wise comparison matrix. Column (B) shows the calculation of the relative weights (Eigenvalue) of a criterion which is equal to the geometric mean of that criterion over the sum of the geometric mean for all criteria. Column (C) shows the vector weight for criteria, which is equal to the sum of multiplying the relative weights by the values in each matrix's row. Column (D) represents the value of λmax, calculated by dividing the vector weight by the relative weight of each criterion.

Table 6.43 Pair-wise comparison matrix and computing of the relative weights

Selction criteria	IC	RC	EIC	SV	SUS
IC	1	2.00	9.00	3.00	5.00
RC	0.5	1	8	2	3
EIC	0.1111	0.125	1	0.125	0.1666
SV	0.3333	0.5	8	1	3
SUS	0.2	0.3333	6	0.3333	1
A	B	C	D	E	F
Geometric Mean	EV wieght	Aω	λ	CI	CR
3.06	0.43	2.23	5.19		
1.89	0.26	1.35	5.10		
0.20	0.03	0.15	5.35		
1.32	0.18	0.96	5.20		
0.67	0.09	0.49	5.28		
7.14	1.00		5.22	0.06	0.05

The calculation of the consistency ratio, shown in columns (E) and (F), is calculated by dividing the consistency index value (CI) by the random consistency index value (CR = CI / RI). The CI is calculated as follows: CI = (λmax – n)/ (n -1), while the RI value is obtained from table 6.44 using a size n matrix. Expert is judged to be unacceptable when CR exceeds 0.10, which indicates inconsistency in the judgment matrix. Some of responses are eliminated due to their high consistency ratio.

Table 6.44 (R.I) Random Inconsistency Index (Saaty 1980)

RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48
n	1	2	3	4	5	6	7	8	9	10	11	12

Thirteen responses passed the consistency test, as shown in table 6.45. The relative weights of the selection criteria are computed for every respondent and the mean, median, mode, and standard deviation are calculated accordingly. The relative weights of the selection criteria are computed based on the mean. The average resulted relative weights are computed as: 25% for initial costs, 33% for running costs, 13% for environmental impact costs, 10% for salvage value, and 19% for sustainability principles.

Table 6.45 Resulted relative weights for the various selection criteria

Selection Criteria	IC	RC	EIC	Sv	SUS	TOTAL
1	0.43	0.27	0.03	0.18	0.09	1.00
2	0.177	0.316	0.269	0.070	0.168	1.00
3	0.115	0.221	0.140	0.065	0.459	1.00
4	0.209	0.276	0.276	0.079	0.159	1.00
5	0.276	0.168	0.200	0.058	0.299	1.00
6	0.387	0.356	0.115	0.030	0.112	1.00
7	0.25	0.52	0.07	0.08	0.08	1.00
8	0.23	0.31	0.13	0.03	0.30	1.00
9	0.300	0.350	0.080	0.120	0.150	1.00
10	0.32	0.35	0.10	0.08	0.15	1.00
11	0.12	0.39	0.03	0.29	0.18	1.00
12	0.17	0.45	0.14	0.07	0.17	1.00
13	0.24	0.28	0.16	0.12	0.19	1.00
Median	0.24	0.32	0.13	0.08	0.17	0.93
Mean	0.25	0.33	0.13	0.10	0.19	1.00
Mode	N/A	0.35	N/A	N/A	0.15	
STDEV	0.094974421	0.092792238	0.078593018	0.070277924	0.10422834	0.44086594

6.10.3.1 Reliability Analysis of Responses

Cronbach's alpha approach is used to perform the reliability analysis of the experts' responses. Cronbach's alpha is a coefficient of reliability that tests internal consistency or reliability of a psychometric test score for a sample of examinees. It describes how well a set of variables measures a single uni-dimensional latent construct. This coefficient is equal the ratio of the true variance to the total variance of a measurement and is a function of a number of observations, variance and covariance. The reliability analysis of data can be assessed using Cronbach's alphas follows:.

$$C\alpha = \frac{n}{n-1}\left(1 - \frac{\Sigma Vi}{\overline{V}}\right)$$

(Equation 6.11)

where:

$\overline{V}$ = sum of variance of overall points

Vi = variance of values for each point

n = number of points

Cronbach's alpha coefficient of reliability has scale value that ranges from 0 - 1. The lower the score, the less reliable is the data. The acceptable reliability range varied between 0.70 and 1.0. A commonly accepted rule of thumb for describing internal consistency using Cronbach's alpha is presented in Table 6.46.

Table 6.46 Accepted rule of thumb for internal consistency (George, 2003)

Cronbach's Alpha (α)	Internal consistency
α ≥ .9	Excellent reliability
.9 > α ≥ .8	Good reliability
.8 > α ≥ .7	Acceptable reliability
.7 > α ≥ .6	Questionable reliability
.6 > α ≥ .5	Poor reliability

The reliability analysis for internal consistency is performed in this study using the SPSS software. The result shows that the data has an excellent reliability according to Cronbach's Alpha (0.908), as presented in Table 6.47 This value could be further increased by eliminating some responses, such as number three, to get α=0.925 as shown in Table 6.48.

Table 6.47 Resulted Cronbach's Alpha value using SPSS

		N	%	Cronbach's Alpha	Based on Standardized Items	N of Items
Cases	Valid	5	100.0	.908	.922	13
	Excluded[a]	0	.0			
	Total	5	100.0			

Table 6.48 Expected Cronbach's Alpha if any single response is eliminated

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
1	2.400108	1.220	.478	.909
2	2.400108	1.272	.594	.904
3	2.400108	1.339	.129	.925
4	2.400108	1.302	.527	.906
5	2.400108	1.332	.308	.912
6	2.400108	1.094	.861	.890
7	2.400108	1.026	.877	.889
8	2.400000	1.182	.803	.895
9	2.400108	1.161	.922	.890
10	2.400108	1.139	.944	.888
11	2.400108	1.286	.328	.914
12	2.400108	1.117	.877	.890
13	2.400108	1.263	.993	.898

6.10.4 Preference Utility Values using the MAUT

The second part of the questionnaire is designed to determine the preference utility values for the selection criteria. This section provides the acceptable and preferred ranges of utility scores for all the weighted criteria described in the first part of the survey. Experts are asked to assign a preference cost value for each utility score on a scale of 0 – 1.0 for various criteria that govern the selection of structure and envelope type. The best values (the extremely-preferred values) are assigned a utility score of 1.0 while the worst values (the least-preferred values) are assigned a utility score of 0. These scores are used in developing the utility curves for the different selection criteria. The developed utility curves include initial costs, running costs, environmental impact costs, and salvage value, as presented in tables 6.49 and 6.50. Five decision makers participated in building the utility curves.

Table 6.49 Preference utility values of selection criteria for elementary schools

Criteria	**Utility scores**					
Initial Costs ($/ft²)	**Respondents**	**0.0**	**0.25**	**0.5**	**0.75**	**1.0**
	1	291	267	243	218	194
	2	388	340	218	175	150
	3	381	286	262	190	125
	4	250	225	200	175	125
	5	350	300	250	200	175
	Avg.	**332**	**283.6**	**234.6**	**191.6**	**153.8**
Running costs ($/ft²)	**Respondents**	**0.0**	**0.25**	**0.5**	**0.75**	**1.0**
	1	110	100	90	80	75
	2	130	115	100	80	75
	3	120	110	100	90	75
	4	130	120	110	100	80
	5	140	130	120	110	70
	Avg.	**126**	**115**	**104**	**92**	**75**

Table 6.50 Preference utility values of selection criteria for high schools

Criteria	Utility scores					
	Respondents	**0.0**	**0.25**	**0.5**	**0.75**	**1.0**
Initial Costs ($/ft²)	1	362	295	222	180	150
	2	344	279	236	190	155
	3	355	286	262	175	150
	4	325	275	250	225	200
	5	300	275	225	200	120
	Avg.	**337.2**	**282**	**239**	**194**	**155**
Criteria	**Utility scores**					
	Respondents	**0.0**	**0.25**	**0.5**	**0.75**	**1.0**
Running costs ($/ft²)	1	110	100	80	70	60
	2	120	100	90	80	70
	3	130	110	100	90	80
	4	110	100	90	80	70
	5	130	120	110	100	75
	Avg.	**120**	**106**	**94**	**84**	**71**
Criteria	**Utility scores**					
	Respondents	**0.0**	**0.25**	**0.5**	**0.75**	**1.0**
Enviro. Impact costs ($/ft²)	**1**	3.25	2.25	2.0	1.25	0.65
	2	3.0	2.5	1.75	1.0	0.75
	3	3.5	1.75	1.5	1.0	0.5
	4	3.0	2.25	2.0	1.5	0.75
	5	3.0	2.75	2.5	1.75	0.5
	Avg.	**3.15**	**2.3**	**1.95**	**1.3**	**0.63**
Criteria	**Utility values**					
	Respondents	**0.0**	**0.25**	**0.5**	**0.75**	**1.0**
Salvage Value ($/ft²)	**1**	10	25	40	50	60
	2	0	20	50	60	80
	3	10	20	30	55	80
	4	0	30	50	70	80
	5	0	20	40	50	70
	Avg.	**4**	**23**	**42**	**57**	**74**

The utility function values of initial costs, running costs, environmental impact costs, and salvage values for elementary and high school buildings are presented in Figures 6.27-6.32. The utility curves are developed by determining of the preferred cost values at each predetermined utility score (0, 0.25, 0.5, 0.75, and 1.0). The best-fitted lines are drawn for each utility function and the equations of the lines are developed accordingly, as shown in the utility graphs.

The utility function values of initial costs for elementary school are illustrated in figure 6.28, where the experts determined their preference values and the acceptable range of initial costs ($153- $332/ft^2).

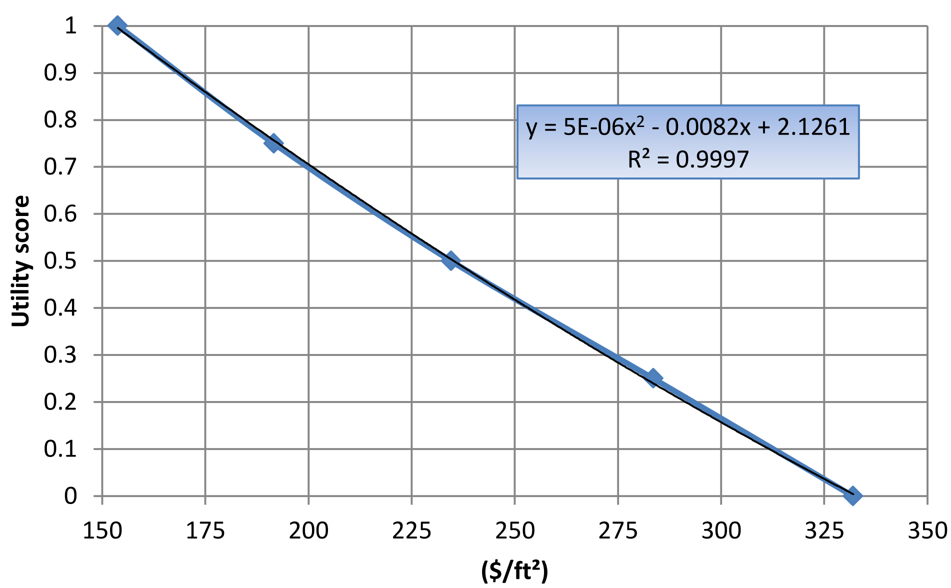


Figure 6.29 Utility values for initial costs in elementary schools

The utility function values of running costs in present value (PV) for elementary schools are illustrated in figure 6.29, where the experts determined their preference values and the acceptable average range of running costs ($75- $126/ft^2).

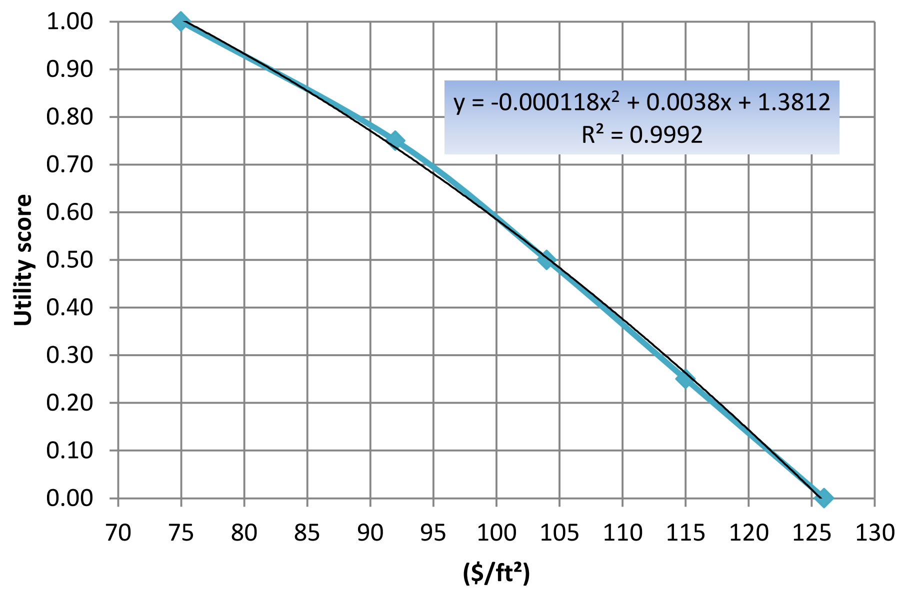


Figure 6.30 Utility values for running costs in elementary schools

The utility function values of salvage value in PV for school buildings are illustrated in figure 6.30, where the experts determined their preference values and the acceptable average range of salvage value ($4- $74/ft^2).

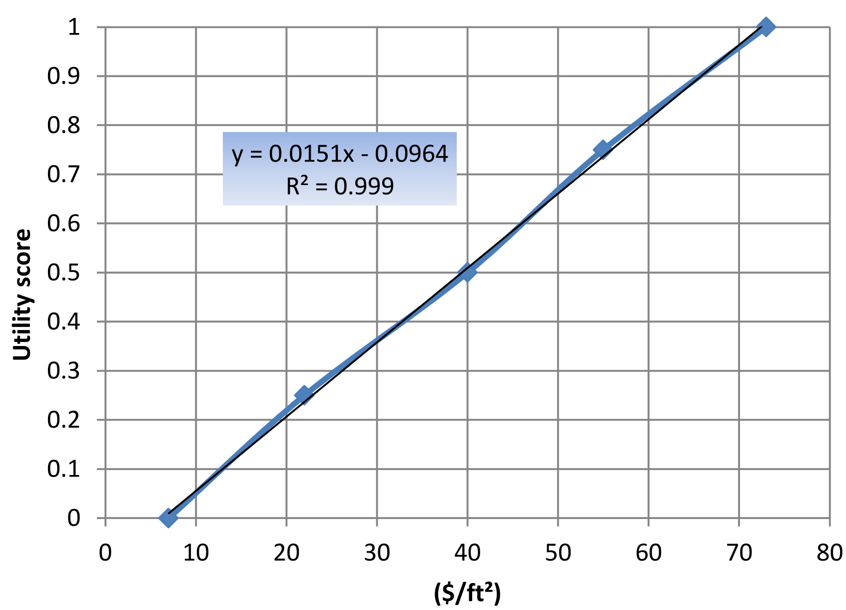


Figure 6.31 Utility values for salvage values in school buildings

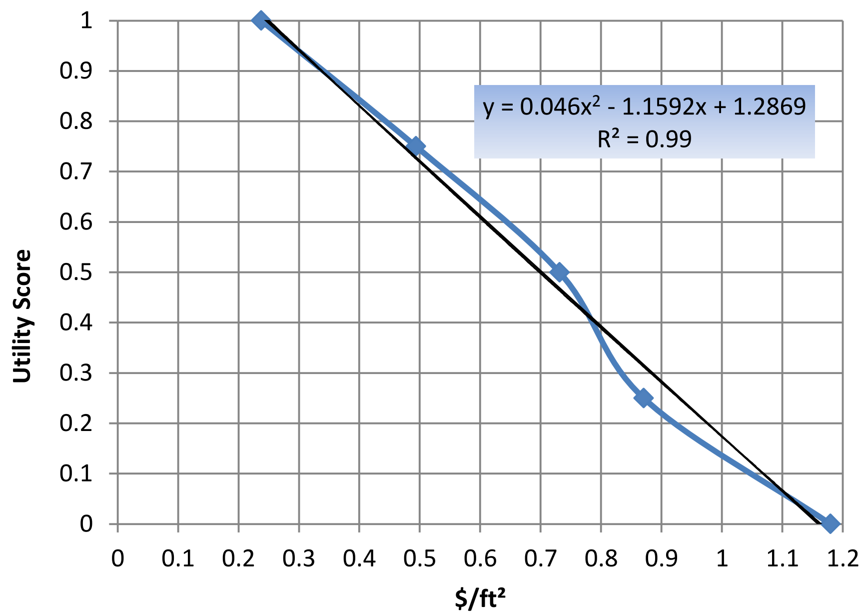


Figure 6.32 Utility values for environmental impact costs

The utility function values of environmental impact costs in PV for school buildings are illustrated in figure 6.31, where the experts determined their preference values and the acceptable average range of environmental impact costs ($0.23- $1.17/ft^2).

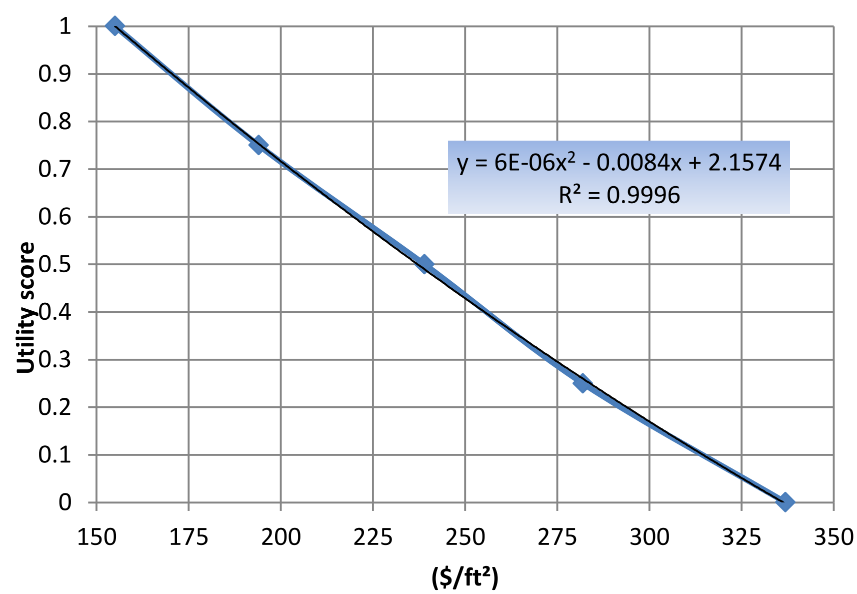


Figure 6.33 Utility values for initial costs in high school buildings

The utility function values of initial costs for high schools are illustrated in figure 6.32, where the experts determined their preference values and the acceptable range of initial costs ($155- $337.5/ft^2).

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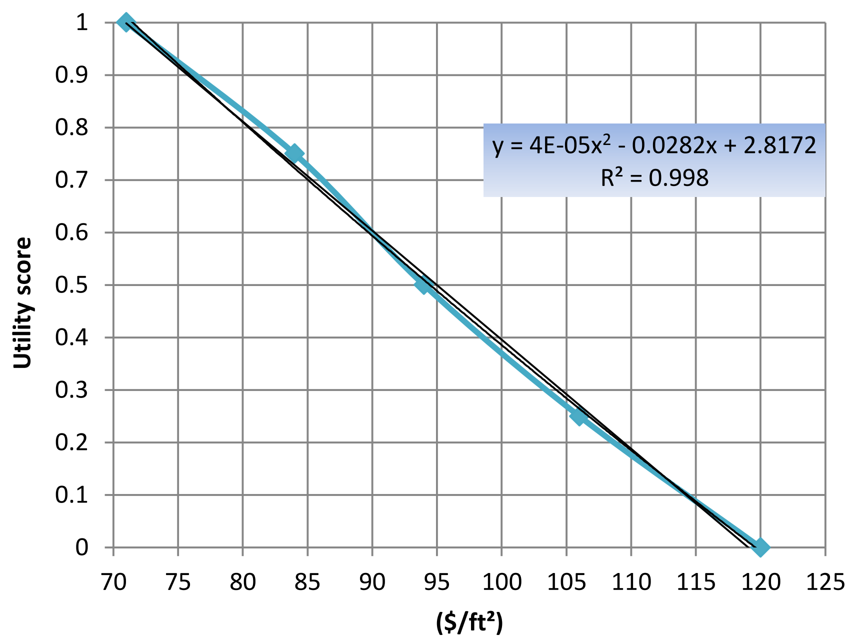


Figure 6.34 Utility values for running costs in high school buildings

The utility function values of running costs in present value (PV) for high schools are illustrated in figure 6.33, where the experts determined their preference values and the acceptable average range of running costs ($71- $120/ft^2).

CHAPTER 7: IMPLEMENTATION OF THE SELECTION FRAMEWORK, AND VALIDATIONS

7.1 Introduction

This chapter presents the implementation and the output of the developed LCC forecasting models and the selection framework in both the deterministic and stochastic approaches. It also shows the area (ft^2) and total LCC components for the different alternatives. The selection is performed using the developed selection framework, using the deterministic, stochastic, and risk assessment approaches.

7.2 Case Study

The analyzed case study is a hypothetical 2-story elementary school building in the city of Montreal in 2011. Table 7.1 presents the general parameters of the tested case study.

Table 7.1 General parameters of the tested hypothetical case study

Parameter	Description	Parameter	Description
School level	Elementary	City	Montreal
Area	105,200 (ft^2)	Discount rate	5%
No of floors	2	Inflation rate	2%
Life span	20 years	Year of construction	2011
Structure type	Test all	End of forecasting	2031

7.3 Deterministic Approach

This approach is applied to compute a LCC and sustainability score in deterministic values that will enable decision makers in school boards to select the best structure and exposure types for their new school buildings.

7.3.1 Results (square footage costs)

Table 7.2 presents the life cycle component costs for each building alternative as a rate per square foot, broken down by type of cost. Comparing Initial costs shows that the lowest initial cost is $136.4/ft^2 for a wood building (WW), while the highest is recorded at $188.1/ft^2 for a concrete building (CC) conventional school building. The costs for conventional steel structures varies between $153.5/ft^2 for pure steel buildings (SS) and $159.5/ft^2 for a steel frame with exterior brick (SC).The result from analyzing sustainable school buildings showed that the average initial costs vary between $232.8/ft^2 for masonry alternative (CM) and $384.5/ft^2 for pure wood buildings (GWW).The lowest annual energy cost for a conventional building is $1.87/ft^2 for concrete facades (CC), while the highest is recorded at $2.01/ft^2 for steel facades (SS). Among the sustainable options, the lowest energy cost is $1.07/ft^2 for steel with wood facades (GSW), and the highest cost is recorded as $1.48/ft^2 for wood frame with brick facades (GWC). Annual operating and maintenance costs are fixed at $3.43/ft^2 as they are not affected by structure and envelope type; however, do vary in sustainable buildings according to the level of sustainability -- between $3.24 and $3.29/ft^2. The lowest annual major repairs cost for conventional buildings is $1.21/ft^2 for concrete structures while the highest is $1.89/ft^2 for wood structures. MR costs vary between $1.13 and$1.73/ft^2 for sustainable school buildings. The lowest environmental impact cost (EIC) after 20 years of operation is recorded at $2.29/ft^2 for conventional concrete (CC) while the highest is recorded for steel building (SS) at $2.72/ft^2. The EIC for sustainable buildings varies between

$1.34/ft^2 and $1.85ft^2 for (GSW) and (GSS).The lowest salvage value after 20 years of operation is recorded at 0 for both (WW) and (GWW), while the highest value is recorded for (CC) and (GCC) at $108.7/ft^2 and $156.9/ft^2, respectively, as presented in table 7.2.

Table 7.2 Life cycle component costs per square foot for the various alternatives

Alternative	IC	EC	O&M	MR	Total RC	SV	EIC
Conventional school building							
SS	$153.54	$2.01	$3.43	$1.69	$7.13	$51.17	$2.72
SC	$159.48	$1.98	$3.43	$1.69	$7.11	$68.26	$2.67
SW	$154.88	$1.97	$3.43	$1.70	$7.10	$51.58	$2.54
WW	$136.45	$1.97	$3.43	$1.89	$7.29	$0.00	$2.56
WC	$141.01	$1.96	$3.43	$1.89	$7.28	$28.20	$2.50
CM	$172.94	$1.90	$3.43	$1.21	$6.54	$95.98	$2.59
CC	$181.16	$1.87	$3.43	$1.21	$6.52	$108.70	$2.29
Sustainable school building							
GSS	$243.95	$1.38	$3.28	$1.56	$6.22	$81.31	$1.85
GSC	$274.58	$1.40	$3.28	$1.56	$6.24	$117.66	$1.84
GSW	$296.77	$1.07	$3.24	$1.54	$5.85	$98.92	$1.34
GWW	$384.59	$1.31	$3.25	$1.72	$6.27	$0.00	$1.66
GWC	$318.42	$1.48	$3.27	$1.73	$6.48	$63.68	$1.82
GCM	$232.86	$1.41	$3.29	$1.13	$5.83	$129.36	$1.80
GCC	$261.58	$1.30	$3.28	$1.13	$5.71	$156.95	$1.47

7.3.2 Life Cycle Costs

Table 7.3 presents the total life cycle component costs for each alternative in Canadian Dollars. The lowest initial cost for conventional schools is recorded at $14.35 million for pure wood school buildings (WW), while the highest cost is $19.0 million for concrete alternative (CC). The initial costs of a conventional steel building vary between $16.1 and 16.8 million for (SS) and (SC) types, respectively. Using a wood frame with a wood façade (WW) will cut costs by $4.7

million and $2.4 million compared to conventional concrete and steel buildings, respectively. The initial costs for sustainable schools vary from $24.5 to 40.4 million for concrete (GCM) and wood schools (GWW), respectively – a difference of 16 million dollars. Even more dramatic is that a conventional wood school would reduce costs by about $ 26 million compared to the sustainable wood option, which indicates that a sustainable wood structure costs 280% more than a conventional wood building.

The lowest annual running costs (RC) for a conventional school is recorded at $686 thousand for a concrete school building (CC), and the highest annual cost is recorded at $766.8 thousand for a pure wood structure (WW). The average annual running costs for a conventional school building is close to $748 thousand, for a steel structure (SC). Using a concrete frame with a precast façade will reduce the annual cost by about $80,000 and $62,000 for conventional wood and steel buildings, respectively. The annual running costs for sustainable schools vary between $600 – 682 thousand, for green concrete schools (GCC), and green wood schools (GWC), respectively. An annual savings of $167,000 in RC can be achieved by choosing a sustainable concrete school (GCC) compared to a conventional wood school (WW).

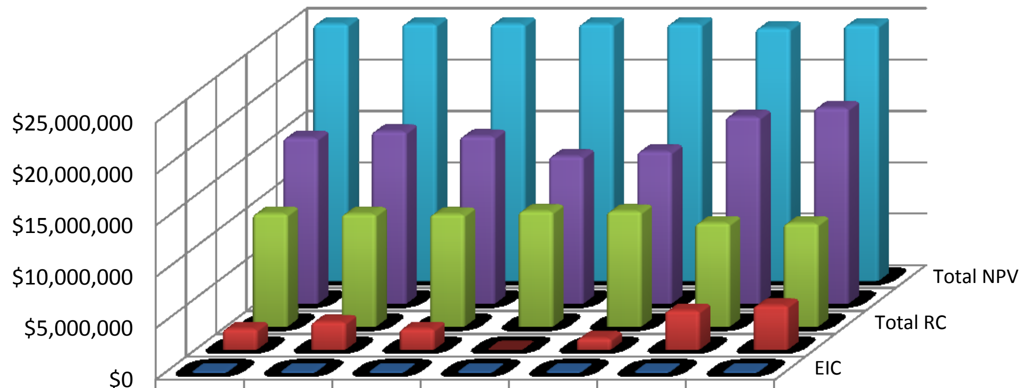
Salvage values are assumed to be computed according to the initial cost, and to be governed only by structure and envelope types since sustainability has not yet been proven to increase building life span or salvage value. After 20 years of operation, the lowest salvage value for conventional and sustainable school buildings is about $0 for pure wood structures. The highest salvage values vary from $11.4 for conventional precast concrete (CC) to $16.5 million for the sustainable version (GCC). The salvage values of steel school buildings vary from $5.3 for conventional steel (SS) to $12.3 million) for sustainable steel schools (GSC). Sustainable school buildings have greater salvage values than conventional ones in part because of the higher initial investments. An eventual gain of $5.1 million is the future savings realizable in the salvage value of sustainable precast concrete (CC) over a similar conventional school design. The environmental impact cost (EIC) is a future penalty that is affected by energy savings. The EIC can only be realized in full after 20 years of a building's operation can be assessed in terms of environmental impact. The lowest EIC of conventional school buildings is indicated for precast concrete (CC) at $240,000, and the highest is $286,000 for pure steel building (SS). Conventional wood structure schools vary from $262 -- $269 thousand for wood frame with brick (WC) and pure wood (WW), respectively. For sustainable schools, the lowest EIC is computed at $141,000 for GSW) and the highest at $195,000 for GSS. The environmental impact costs could be cut in half (from $286 – $141 thousands) by applying sustainability principles, as can be seen in Table 7.3.

Table 7.3 Total life cycle components' costs for the various alternatives

Alternative	IC	EC	O&M	MR	Total RC	SV	EIC
				Conventional school building			
SS	$16,152,408	$211,136	$360,836	$178,314	$750,286	$5,383,598	$285,934
SC	$16,777,296	$209,138	$360,836	$178,314	$748,288	$7,180,683	$281,200
SW	$16,293,376	$207,454	$360,836	$178,314	$746,604	$5,425,694	$266,682
WW	$14,354,540	$207,454	$360,836	$198,512	$766,803	$0	$269,733
WC	$14,834,252	$206,718	$360,836	$198,512	$766,066	$2,966,850	$262,579
CM	$18,193,288	$199,985	$360,836	$127,608	$688,429	$10,097,275	$272,678
CC	$19,058,032	$197,566	$360,836	$127,608	$686,009	$11,434,819	$240,803
				Sustainable school building			
GSS	$25,663,093	$145,344	$344,869	$164,007	$654,220	$8,554,279	$194,645
GSC	$28,886,055	$146,887	$344,752	$164,322	$655,962	$12,377,675	$193,446
GSW	$31,220,307	$112,657	$340,766	$161,798	$615,220	$10,406,665	$140,721
GWW	$40,458,887	$138,056	$341,435	$180,418	$659,909	$0	$174,374
GWC	$33,497,846	$155,904	$344,242	$181,996	$682,142	$6,699,569	$191,683
GCM	$24,496,711	$148,029	$346,346	$119,192	$613,566	$13,609,148	$189,000
GCC	$27,517,840	$137,110	$345,004	$118,455	$600,569	$16,510,704	$154,636

7.3.3 Total Life Cycle Costs in NPV

Figure 7.1 presents the life cycle costs and total net present values (NPVs) for conventional school buildings. The result of LCC analysis for conventional school buildings shows that initial costs represent the major impact on the total net present value. The initial costs represent from 56% to 79% of the total NPV for wood (WW) and precast concrete (CC) schools, respectively. The total present value of annual cost represents the second-highest contribution to the total present value. Its impact varies from 40% for precast (CC) to 44% for wood schools (WW). The lowest impact is that of the environmental impact cost, because it is a future cost that will be spent after 20 years of operation. The minimum computed total net present values range from $24.9 for precast concrete schools (CC) to $25.7 million for wood school buildings (WW). A maximum of $800,000 could be saved by choosing a precast concrete (CC).



	SS	SC	SW	WW	WC	CM	CC
EIC	$107,765	$105,981	$100,510	$101,659	$98,963	$102,769	$90,756
SV	$2,029,0	$2,706,3	$2,044,8	$0	$1,118,1	$3,805,5	$4,309,6
Total RC	$11,003,	$10,973,	$10,949,	$11,245,	$11,234,	$10,096,	$10,060,
IC	$16,152,	$16,777,	$16,293,	$14,354,	$14,834,	$18,193,	$19,057,
Total NPV	$25,234,	$25,151,	$25,298,	$25,701,	$25,049,	$24,586,	$24,899,

Figure 7.1 Life cycle costs and total net present value for conventional school buildings

Figure 7.2 presents the life cycle costs and total net present value for sustainable school buildings. The result of LCC analysis for sustainable school building shows that, as with conventional buildings, initial costs apparently have the highest impact on the total net present value. The initial costs represent approximately 80 to 92% of the total NPV for wood (GWW), and precast concrete (GCC) schools, respectively. The total present value of annual cost contributes the second-highest cost impact on the total present value. Its impact ranges from 19% for wood schools (GWW) to 30% for steel schools (GSS). The minimum computed total net present values range from $30.1 million for precast concrete (GCC) to $50.2 million for wood schools (GWW). A total of $20 million could be saved by choosing precast concrete (GCC) instead of using a sustainable wood school building (GWW).

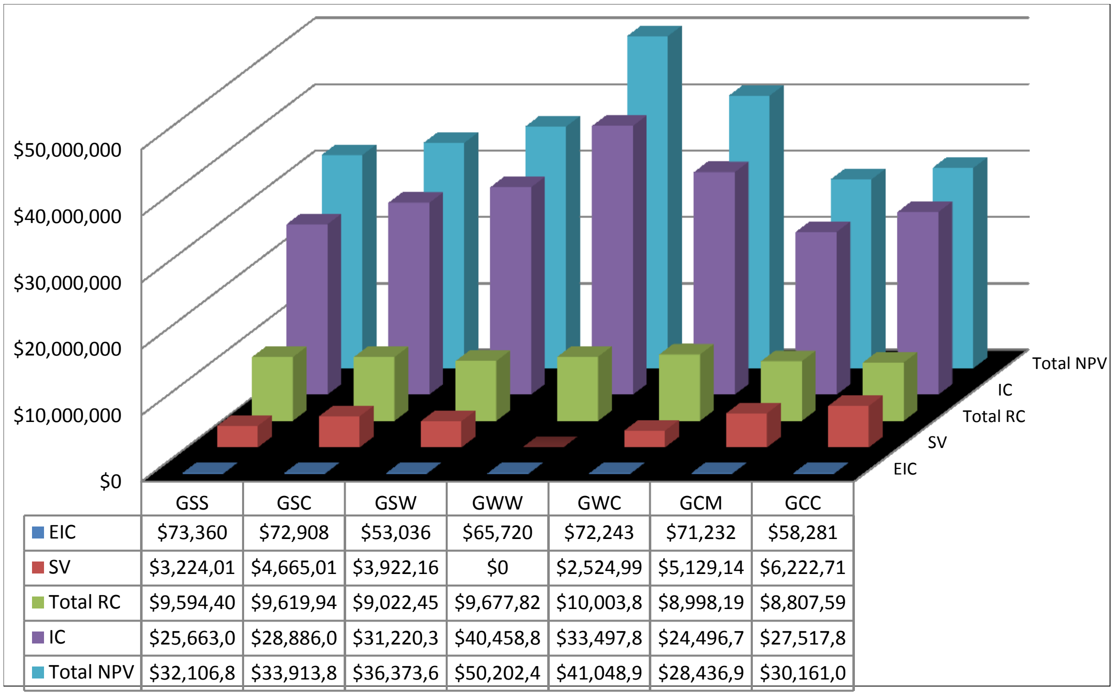


Figure 7.2 Life cycle costs and total net present value for sustainable school buildings

Applying sustainability principles to conventional structure and envelope types increase the total NPV cost. These increases range between 16% and 100% for green concrete with masonry wall schools (GCM) to green wood school buildings.

7.3.4 Measuring the Economic Performance of Alternatives

The selection of structure and envelope types is performed using the present value per square footage for each LCC component, which has been evaluated and ranked by experts. Table 7.4 presents the PV of LCC components and the total NPV per square foot.

Table 7.4 Present values of LCC components and the overall NPV for alternatives, per square foot

Alternative	IC	EC	O&M	MR	Total RC	SV	EIC	NPV
Conventional school building								
SS	$153.54	$29.43	$50.30	$24.86	$104.59	$19.29	$1.02	$239.87
SC	$159.48	$29.15	$50.30	$24.86	$104.32	$25.73	$1.00	$239.08
SW	$154.88	$28.92	$50.30	$24.86	$104.08	$19.44	$0.95	$240.48
WW	$136.45	$28.92	$50.30	$27.67	$106.90	$0.00	$0.96	$244.31
WC	$141.01	$28.81	$50.30	$27.67	$106.79	$10.63	$0.94	$238.12
CM	$172.94	$27.87	$50.30	$17.79	$95.97	$36.17	$0.98	$233.71
CC	$181.16	$27.54	$50.30	$17.79	$95.63	$40.97	$0.86	$236.69
Sustainable school building								
GSS	$243.95	$20.26	$48.08	$22.86	$91.20	$30.65	$0.70	$305.20
GSC	$274.58	$20.48	$48.06	$22.91	$91.44	$44.34	$0.69	$322.38
GSW	$296.77	$15.70	$47.50	$22.56	$85.76	$37.28	$0.50	$345.76
GWW	$384.59	$19.25	$47.60	$25.15	$91.99	$0.00	$0.62	$477.21
GWC	$318.42	$21.73	$47.99	$25.37	$95.09	$24.00	$0.69	$390.20
GCM	$232.86	$20.64	$48.28	$16.62	$85.53	$48.76	$0.68	$270.31
GCC	$261.58	$19.11	$48.10	$16.51	$83.72	$59.15	$0.55	$286.70

7.3.4.1 Initial Costs

Figure 7.3 presents the initial costs per square foot for the 14 structure and envelope type alternatives for conventional and sustainable school buildings. These figures indicate that the initial costs for the computed conventional structure and envelope types are less than the costs for sustainable options. The minimum initial cost is $136/ft^2 for a conventional wood school (WW), and the maximum is $384/ft^2 for a green wood school (GWW) – a 180% higher cost than the conventional option. The maximum initial cost of a conventional school is $181/ft^{2}for precast concrete (CC), which is 33% more than for the wood system (WW). The minimum initial cost of the sustainable alternatives is $232/ft^2 for a concrete school with the cavity wall system (GCM). Applying the minimum initial cost sustainable option, (GCM), will increase the cost by 28% and 70% over the conventional alternatives (CC) and (WW), respectively, as shown in figure 7.3

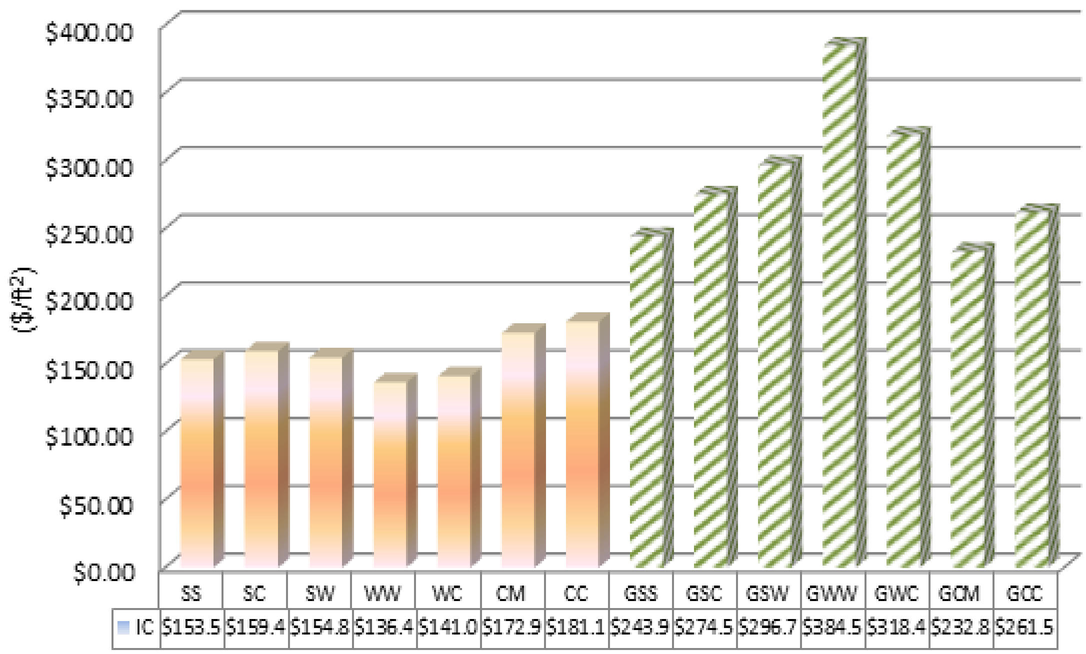


Figure 7.3 Comparison of the square footage initial costs for the tested alternatives

Table 7.5 presents the alternatives, utility scores, the weights of criteria for initial costs and for running costs, and the total scores. The selection of the most favorable structure and envelope type among these alternatives is done using the MAUT and the AHP, based on the selection criteria. Utility scores of initial costs are computed for the different alternatives based on experts' opinions and using a MAUT graph which is represented by the following equation:

$$y = 5 \times 10^{-6} X^2 - 0.0082X + 2.126 \qquad \text{(Equation 7.1)}$$

If the utility score is equal or close to 1.0, it means that this alternative meets the preferences of experts and vice versa. The experts gave the initial costs criterion

25% of the relative weight compared to the other criteria. Multiplying a criterion's weight by the performance of each alternative (utility score) results in the total score, as shown in Table 7.5. The best initial cost score is 25.0 for both conventional wood (WW) and (WC), while is the worst is 0.0 for the sustainable wood option (GWW).

Table 7.5 Utility scores, criteria weight, and total scores for initial and running costs

IC	Utility score	criteria weight	Total score	No.	Alternative	RC	Utility score	criteria weight	Total score
$153.54	0.99	AHP Initial Costs 25%	24.64	1	SS	$104.59	0.49	AHP Running Costs 33%	16.10
$159.48	0.95		23.64	2	SC	$104.32	0.49		16.29
$154.88	0.98		24.40	3	SW	$104.08	0.50		16.45
$136.45	1.00		25.00	4	WW	$106.90	0.44		14.49
$141.01	1.00		25.00	5	WC	$106.79	0.44		14.56
$172.94	0.86		21.44	6	CM	$95.97	0.66		21.75
$181.16	0.80		20.12	7	CC	$95.63	0.67		21.96
$243.95	0.42		10.58	8	GSS	$91.20	0.75		24.63
$274.58	0.25		6.29	9	GSC	$91.44	0.74		24.48
$296.77	0.13		3.32	10	GSW	$85.76	0.84		27.69
$384.59	0.00		0.00	11	GWW	$91.99	0.73		24.16
$318.42	0.02		0.55	12	GWC	$95.09	0.68		22.29
$232.86	0.49		12.19	13	GCM	$85.53	0.84		27.82
261.58	0.32		8.08	14	GCC	$83.72	0.87		28.78

7.3.4.2 Running Costs

Figure 7.4 presents the square footage PV of running costs for both conventional and sustainable school buildings over 20 years. The results of these running costs show that the costs of the seven sustainable structure and envelope types are all less than the RCs of the conventional alternatives. The minimum value is recorded at $\$83.7/ft^2$ for green precast concrete schools (GCC), while the maximum RC is $\$106.9/ft^2$ for conventional wood school buildings (WW). The conventional wood school alternative costs close to 28% more to operate than a green concrete school (GCC). The maximum running cost of a sustainable school is found to be \$95.09/ft^{2}for the wood school alternative (GWC). Applying the wood system with exterior brick will increase the running costs by 14% over the precast system (CC). The minimum running cost among the conventional is the \$95.6/ft^2 for precast concrete schools (CC). Applying this minimum running cost conventional alternative (CC) will increase the running costs by 0.6% and 14% over the sustainable alternatives (GWC) and (GCC), respectively, as shown in Figure 7.4

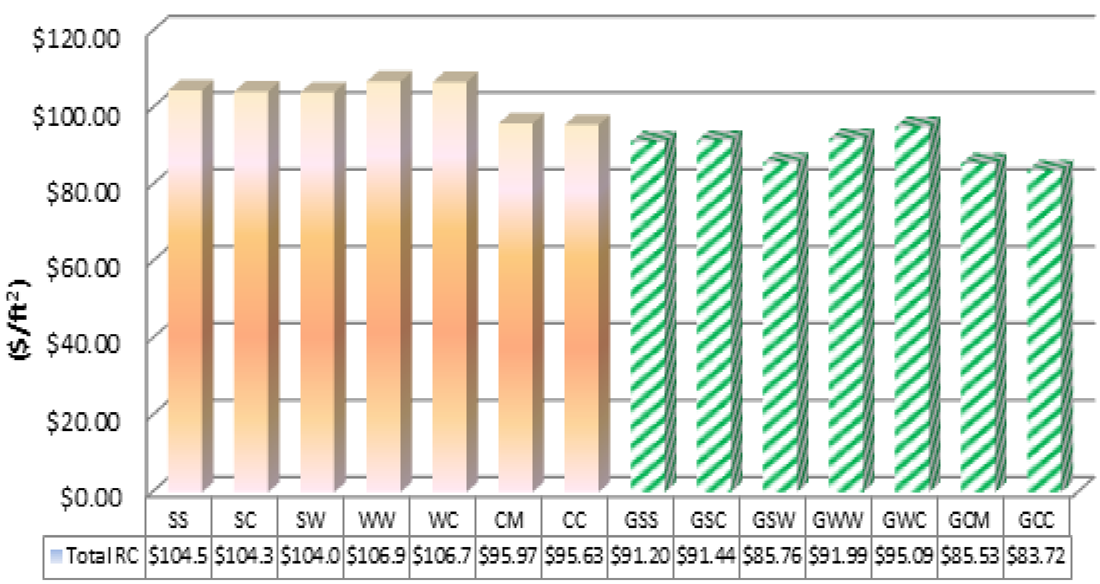


Figure 7.4 PV per square foot of running costs for the various alternatives

A utility score of running costs is computed for the different alternatives, based on experts' opinions and using a MAUT graph, given in the following equation:

$$y = 1.18 \times 10^{-4} X^2 + 0.0038X + 1.381 \qquad \text{(Equation 7.2)}$$

Experts ranked the running costs' criterion as the most important factor, earning it a 33% compared to the other criteria. The best running cost scores for the various alternatives are 28.78 and 27.82, for sustainable precast concrete (GCC) and sustainable and green concrete with cavity wall (GCM) buildings, respectively, while the worst score is 14.49 for the conventional wood school (WW) option, as presented in table 7.5.

7.3.4.3 Environmental Impact Costs (EIC)

Figure 7.5 presents the present value (PV) per square foot of the environmental impact costs for conventional and sustainable school buildings after 20 years. The result of the EIC analysis shows that the costs of the seven computed sustainable structure and envelope types apparently are less than those for conventional options. The minimum value is recorded as $\$0.5/ft^2$ for the green steel with exterior wood school (GSW) option, while the maximum is $\$1.02/ft^2$ for a conventional steel school (SS). The conventional steel school costs close to 104% more than a green steel school (GSW) when accounting for the EIC. The maximum EIC for a sustainable school is $\$0.70/ft^2$for a green steel school (GSS). Applying this green all-steel system will increase the EIC by 40% over the lowest EIC option, steel with exterior wood (GSW). The minimum EIC of all the conventional alternatives is $\$0.86/ft^2$ for a precast concrete school (CC). Applying the conventional alternative with the minimum EIC (CC) will increase the cost by 23% and 72% over the sustainable alternatives with the maximum and minimum cost -- (GSS) and (GSW), respectively, shown in Figure 7.5

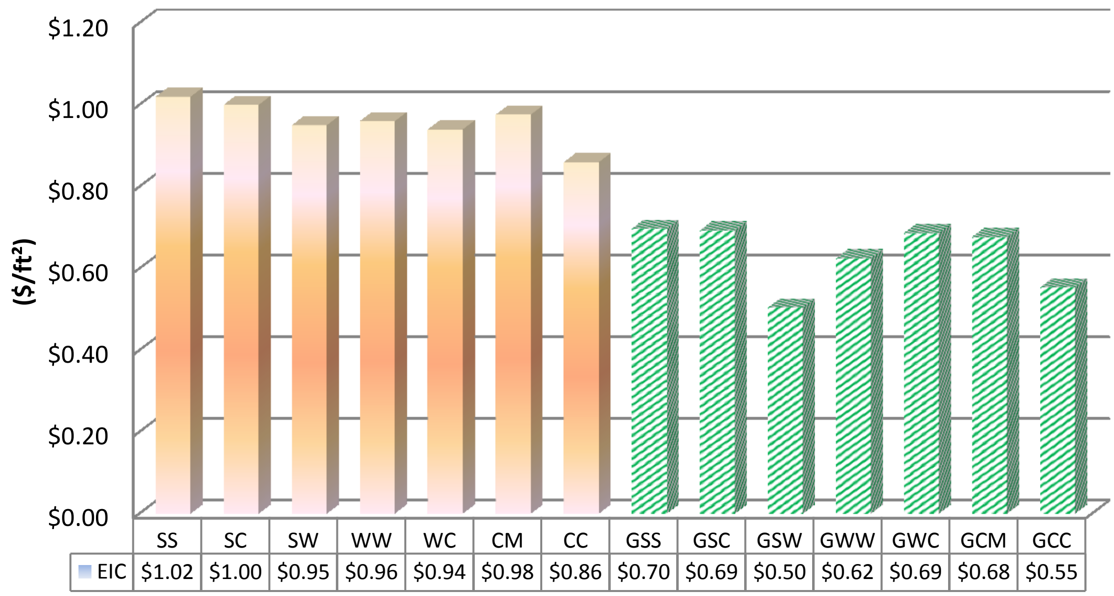


Figure 7.5 PV of environmental impact costs per square foot of the various alternatives

Table 7.6 presents the alternatives, utility scores, weights of criteria for environmental impact costs, salvage values, and total obtained scores. The utility EIC scores were computed for the different alternatives based on experts' opinions using the MAUT graph represented in the following equation:

$$\boldsymbol{y = 0.046X^2 - 1.159X + 1.286} \qquad \text{(Equation 7.3)}$$

The experts ranked the environmental impact cost's criterion at 13% compared to the other selection criteria. The best EIC scores for the various alternatives are 9.28 and 8.56 for sustainable steel school with wood walls (GSW) and sustainable precast concrete (GCC), respectively, while the worst score is 1.98, for conventional steel schools (SS), as presented in Table 7.6.

Table 7.6 Obtained utility scores, criteria weights, and total scores for environmental impact costs and salvage values

EIC	Utility score	criteria weight	Total score	Alternative	SV	Utility score	criteria weight	Total score
$1.02	0.15	AHP Enviro. Impact costs 13%	1.98	SS	$19.29	0.19	AHP Running Costs 10%	1.95
$1.00	0.17		2.26	SC	$25.73	0.29		2.92
$0.95	0.23		2.95	SW	$19.44	0.20		1.97
$0.96	0.22		2.81	WW	$0.00	0.00		0.00
$0.94	0.24		3.09	WC	$10.63	0.06		0.64
$0.98	0.20		2.59	CM	$36.17	0.45		4.50
$0.86	0.32		4.21	CC	$40.97	0.52		5.22
$0.70	0.50		6.51	GSS	$30.65	0.37		3.66
$0.69	0.51		6.57	GSC	$44.34	0.57		5.73
$0.50	0.71		9.28	GSW	$37.28	0.47		4.67
$0.62	0.58		7.55	GWW	$0.00	0.00		0.00
$0.69	0.51		6.66	GWC	$24.00	0.27		2.66
$0.68	0.52		6.80	GCM	$48.76	0.64		6.40
$0.55	0.66		8.56	GCC	$59.15	0.80		7.97

7.3.4.4 Salvage Value

Figure 7.6 presents the square footage PV of salvage values for conventional and sustainable school buildings after 20 years of usage. Some sustainable alternatives have higher salvage values than similar conventional ones due to their higher initial costs. However, some conventional alternatives, such as the concrete systems (CC) and (CM) represent higher salvage values compared to comparable sustainable ones, due to the anticipated long life span of concrete schools. The maximum salvage value is recorded at \$59.1/ft^2 for green precast schools (GCC), while the minimum is recorded at \$0.0/ft^2 for conventional and sustainable wood schools ((WW) and (GWW)). The highest salvage values are \$48.7/ft^2 and \$44.3/ft^2 for sustainable alternatives (GCM) and (GSC), respectively. The next-highest salvage value is \$40.9/ft^2 for conventional precast concrete schools (CC).

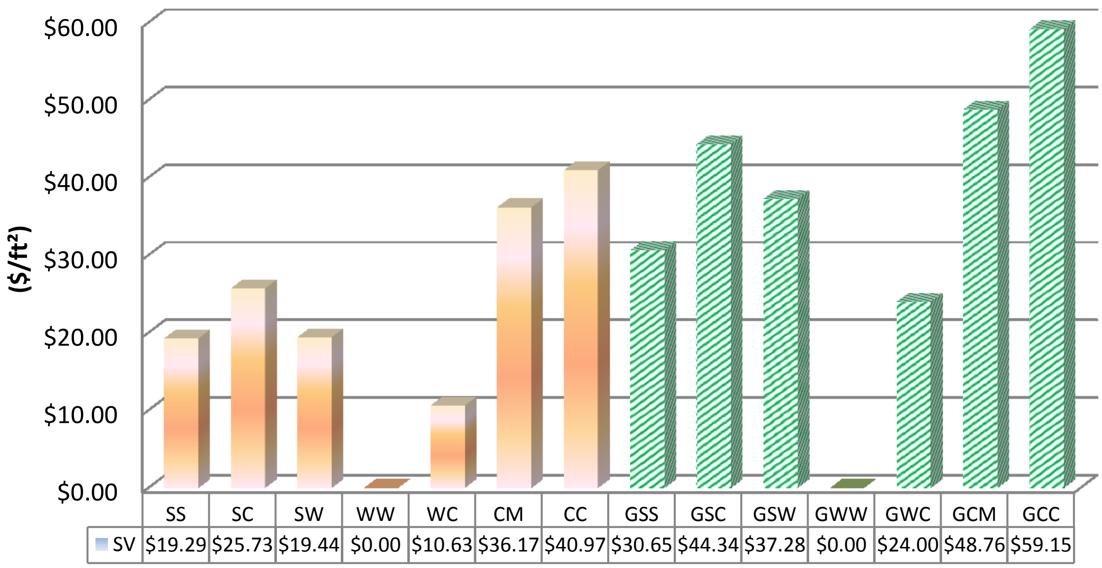


Figure 7.6 The PV salvage values for the various alternatives

The utility scores of salvage values were computed for the different alternatives based on experts' opinions using MAUT graph represented by the following equation:

$$y = 0.0151X - 0.0964 \qquad \text{(Equation 7.4)}$$

The experts ranked the future salvage value criterion at 10% compared to the other selection criteria. The best salvage value scores for the various alternatives are 7.97 and 6.40 for sustainable precast concrete schools (GCC) and concrete frame with cavity walls (GCM), respectively, while the worst score is 0.00 for conventional and sustainable pure wood -- (WW) and (GWW), as presented in Table 7.6.

7.3.4.5 Sustainability

Figure 7.7 presents the expected LEED scores for the conventional school buildings and the scores for the actual LEED certified school buildings. Since the conventional alternatives are evaluated in this study using the sustainability assessment model developed based on three categories of LEED, the conventional alternatives obviously receive lower LEED scores compared to their sustainable counterparts, as indicated in Figure 7.7. The average of the LEED scores for sustainable schools shows that the alternatives are ranked between silver and gold LEED certification levels. The maximum LEED score is recorded at 46 for a sustainable steel with exterior wood wall school (GSW), followed by 42 for green wood schools (GWW), 39 for (GWC), 38 for both (GSS) and (GSC) structures, 36 for (GCC), and 35 for (GCM). The maximum LEED score among the conventional alternatives is 19 for precast concrete schools, and the minimum is 14 for steel schools (SS) and (SC). Applying sustainability principles on the precast concrete school will increase the sustainability level by up to 89%.

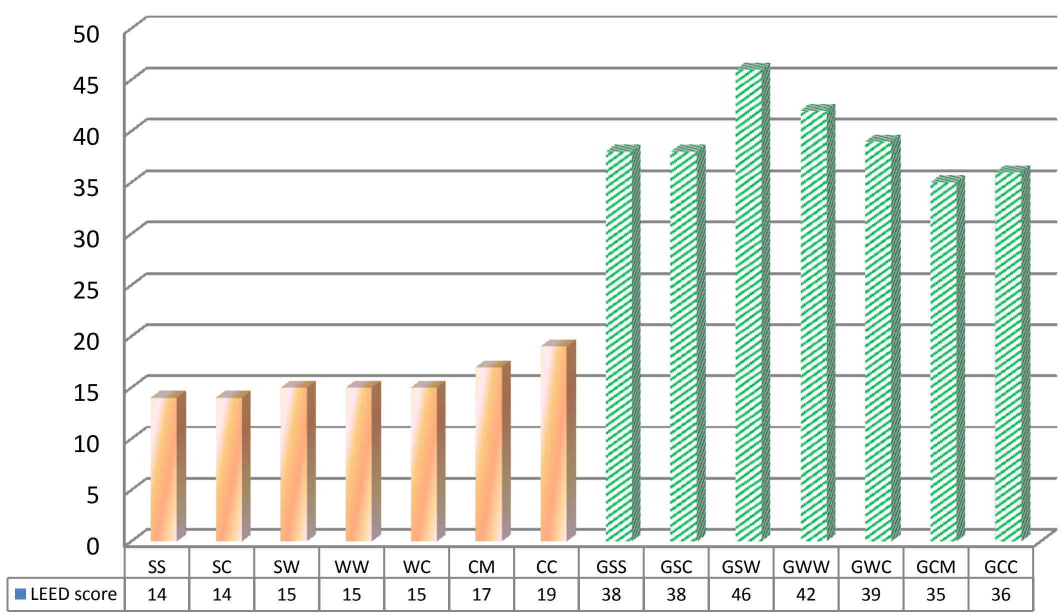


Figure 7.7 LEED's scores of various conventional and sustainable alternatives

Table 7.7 presents the utility scores of each alternative, the weight of sustainability criterion, and the total obtained scores. The sustainability utility scores were computed for the different alternatives based on a linear correlation between LEED score or sustainability and the utility score, which is represented by the following equation:

$$y = \mathbf{0.0179}X \qquad \text{(Equation 7.5)}$$

The experts ranked the sustainability criterion at 19% compared to the other selection criteria. The best sustainability scores the various alternatives are 15.6 and 14.3 for sustainable steel schools with exterior wood walls (GSW) and sustainable wood schools (GWW) respectively, while the worst score is 4.76 for both conventional steel (SS) and conventional steel and concrete schools (SC), as presented in Table 7.7.

Table 7.7 LEED score, utility score, and total obtained score, by alternatives

No.	Alternative	Sustainability LEED® Score	MAUT Utility score	criteria weight	Total score
1	SS	14	0.2506	AHP Sustainability 19%	4.76
2	SC	14	0.2506		4.76
3	SW	15	0.2685		5.10
4	WW	15	0.2685		5.10
5	WC	15	0.2685		5.10
6	CM	17	0.3043		5.78
7	CC	19	0.3401		6.46
8	GSS	38	0.6802		12.92
9	GSC	38	0.6802		12.92
10	GSW	46	0.8234		15.64
11	GWW	42	0.7518		14.28
12	GWC	39	0.6981		13.26
13	GCM	35	0.6265		11.90
14	GCC	36	0.6444		12.24

7.3.4.6 Total Net Present Values (NPV)

Figure 7.8 presents the amounts per square foot of the total NPV of the LCCs for the 14 structure and envelope type alternatives. The NPV results show that the all seven of the conventional alternatives are more cost effective than the sustainable types explored here. The minimum NPV is recorded at $\$233/ft^2$ for concrete schools (CM), while the maximum is $\$477/ft^2$ for green wood schools (GWW). The sustainable wood school option costs almost 105% more than a conventional concrete structure. The maximum NPV of a conventional school is $\$244/ft^2$for a pure wood structure (WW). Applying the conventional wood system will increase the NPV by 5% over the concrete system (CM). The minimum NPV among the sustainable alternatives is recorded at $\$270/ft^2$ for a concrete alternative with cavity wall system (GCM). Applying this alternative will increase the cost by 11% and 16% over the conventional alternatives (WW) and (CM), respectively, with their maximum and minimum NPV as shown in Figure 7.8

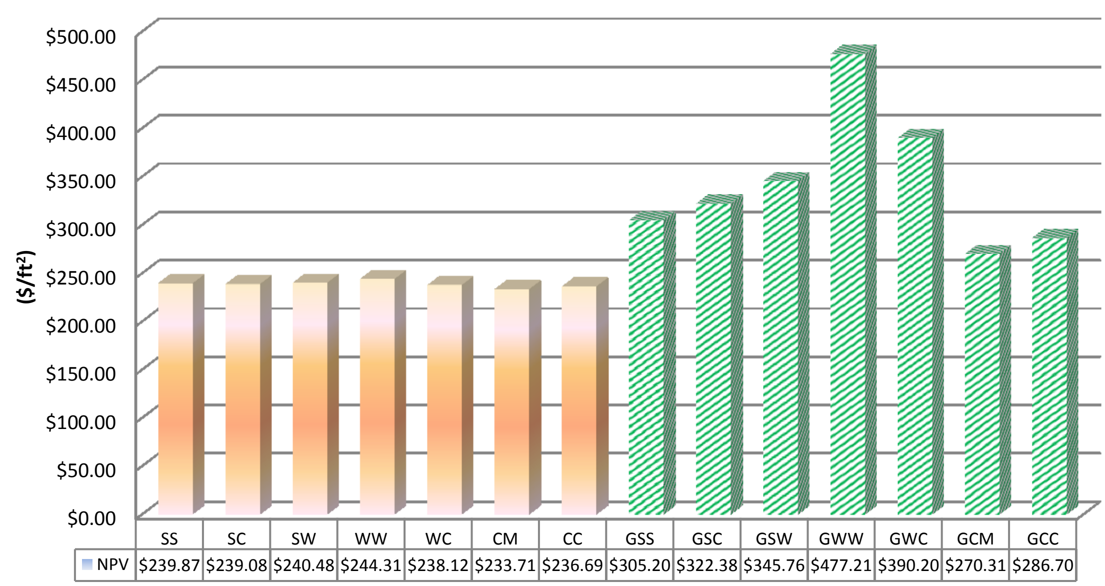


Figure 7.8 Overall NPV per square foot of the alternatives tested

7.3.5 Selection of the Most Favorable Alternatives based on a Deterministic Approach

Table 7.8 presents the total NPVs for all the alternatives, and the overall utility scores. The alternatives are ranked using both the NPV and the developed selection framework. The NPV ranking shows that overall; the conventional alternatives are more cost effective compared to the sustainable alternatives. The conventional alternatives occupy the first seven ranks, which indicate that the sustainable alternatives would be eliminated from possible selection according to the NPV method. The sustainable concrete systems are ranked in 8th and 9th, for GCM and GCC structures, respectively, followed by the steel options (GSS) and (GSW) and then ending with the green wood systems (GWC) and (GWW) in the last two ranks at 13th and 14th , as shown in table 7.8.

Table 7.8 Comparison of rankings for different alternatives using the NPV method and the developed selection framework

No.	Alternative	Overall NPV	Ranking Based on NPV	Overall Utility score	Ranking based on framework
1	SS	$239.87	5	49.38	10
2	SC	$239.08	4	50.34	9
3	SW	$240.48	6	51.51	8
4	WW	$244.31	7	47.44	12
5	WC	$238.12	3	48.66	11
6	CM	$233.71	1	56.04	7
7	CC	$236.69	2	57.89	5
8	GSS	$305.20	10	58.19	4
9	GSC	$322.38	11	56.06	6
10	GSW	$345.76	12	60.51	3
11	GWW	$477.21	14	46.20	13
12	GWC	$390.20	13	45.34	14
13	GCM	$270.31	8	64.70	2
14	GCC	$286.70	9	65.17	1

According to the developed selection framework, the overall utility scores are computed by adding up the total scores obtained for the various alternatives in all the selection criteria: initial costs, running costs, environmental impact costs, salvage values, and sustainability. The results of the selection framework show that the ranking of the alternatives is completely different than that of the NPV method. In this framework, the ranking is performed based on the experts' preferences and the performance of the alternatives across all the criteria measured. The highest score achieved with this method is 65.1 out of 100, while the lowest is 45.4. The top three ranks are occupied by sustainable alternatives, with a 65.1 for green precast concrete (GCC), 64.7 for green concrete with cavity walls (GCM), and 60.5 for green steel with wood walls (GSW). The 5th and 7th ranks are occupied by conventional concrete types; 57.8 points for CC and 56.0 for CM, respectively. The 4th and 6th ranks are filled by sustainable steel systems; 58.1 for GSS and 56.0 for GSC structures. The next-ranking alternatives are conventional steel systems - SW, SC and SS at 8th to10th place. The last four ranks are occupied by conventional and sustainable wood schools with higher rankings for conventional types.

7.4 Stochastic Approach

In this approach, the life cycle cost components are estimated for the various alternatives and presented using probability distribution and cumulative curves (not crisp values or deterministic numbers). Monte Carlo simulation is applied to model the uncertain quantities in the LCC prediction models with probabilistic input. The results are observed at three different confidence levels: 95%, 70%, and 50% (median), to measure their impacts on selection decisions. The selection of alternatives is performed according to the required confidence level by decision makers in regards to their acceptable level of risk. The cost for each alternative is determined at each level of confidence and plotted on the utility graph, and the minimum utility score is estimated accordingly.

7.4.1 Input Data

The input data consists of the life cycle cost components such as initial costs, running costs, environmental impact costs, and salvage values as well as LCC general parameters such as the discount and inflation rate. Most of the cost data is entered as part of a triangular probability distribution function, with the most likely, maximum and minimum cost value. Initial cost parameters such as area and the number of floors are entered in discrete uniform distribution, as presented in Table 7.9. Other costs such as major repair costs and particular sustainable school data are entered using the Best Fit distributions. General LCC parameters are entered using the triangular probability distribution. Tables 7.9 and 7.10, display the input data with their distributions.

Table 7.9 Inputted distribution functions of the area & number of floors

Criterion	Alternative	Area		No of floor		Function type
		Min. (ft^2)	Max. (ft^2)	Min.	Max.	
Initial Costs	CC	15,000	200,000	1	4	Discrete uniform
	CM	15,000	200,000	1	4	Discrete uniform
	SS	15,000	200,000	1	4	Discrete uniform
	WC	15,000	200,000	1	4	Discrete uniform
	WW	15,000	200,000	1	4	Discrete uniform
	SC	15,000	200,000	1	4	Discrete uniform
	SW	15,000	200,000	1	4	Discrete uniform

Table 7.10 Inputted distribution functions for LCC components and parameters

Criterion	Alternative	Function description			Distribution type
		Minimum ($/ft^2)	Most likely ($/ft^2)	Maximum ($/ft^2)	
Energy costs	CC	1.28	1.88	2.48	Triangular
	CM	1.30	1.90	2.50	Triangular
	SS	1.40	2.01	2.60	Triangular
	WC	1.37	1.97	2.57	Triangular
	WW	1.37	1.97	2.57	Triangular
	SC	1.39	1.99	2.59	Triangular
	SW	1.37	1.97	2.57	Triangular
O & M costs	All	2.80	3.43	4.0	Triangular
Inflation rate (j)	All	1.0%	2.0%	3.0%	Triangular
Salvage Values (SV)	CC	50%	60%	70%	Triangular
	CM	45%	56%	65%	Triangular
	SS	25%	33%	41%	Triangular
	WC	10%	20%	30%	Triangular
	WW	-10%	0%	15%	Triangular
	SC	33%	43%	53%	Triangular
	SW	25%	33%	41%	Triangular
Discount rate (i)	All	2.0%	5.0%	8.0%	Triangular
Environ. Impact Costs (EIC)	CC	1.83	2.29	2.74	Triangular
	CM	2.08	2.60	3.12	Triangular
	SS	2.17	2.72	3.26	Triangular
	WC	1.99	2.49	2.99	Triangular
	WW	2.05	2.57	3.08	Triangular
	SC	2.14	2.67	3.20	Triangular
	SW	2.02	2.53	3.03	Triangular

7.5 Output Information

This section elaborates on the stochastic output of life cycle component costs and the overall selection criteria. It also presents the process for the selection of alternatives based on a stochastic selection framework and risk assessment.

7.5.1 Initial Costs (IC)

Figure 7.9 presents the probability distribution of three different alternatives, which here include steel, concrete, and wood school in both cases, conventional and sustainable. Beta PERT distribution is the best fit for the initial costs of a conventional school building. The following probability functions can be the best fit of the initial costs of sustainable alternatives: Lognormal and Max Extreme.

The initial cost statistics for conventional and sustainable alternatives are summarized in tables 7.11 and 7.12 respectively. The statistical information includes mean, median, mode, standard deviation, variance, skewness, kurtosis, coefficient of variability, minimum and maximum values, 5% percentile, 50% percentile, 70% percentile, and 95% percentile. The minimum mean value is recorded for conventional pure wood schools, (WW) at \$137.1 /ft^2, while the maximum value comes to \$386.2 /ft^2 for a sustainable wood school (GWW).

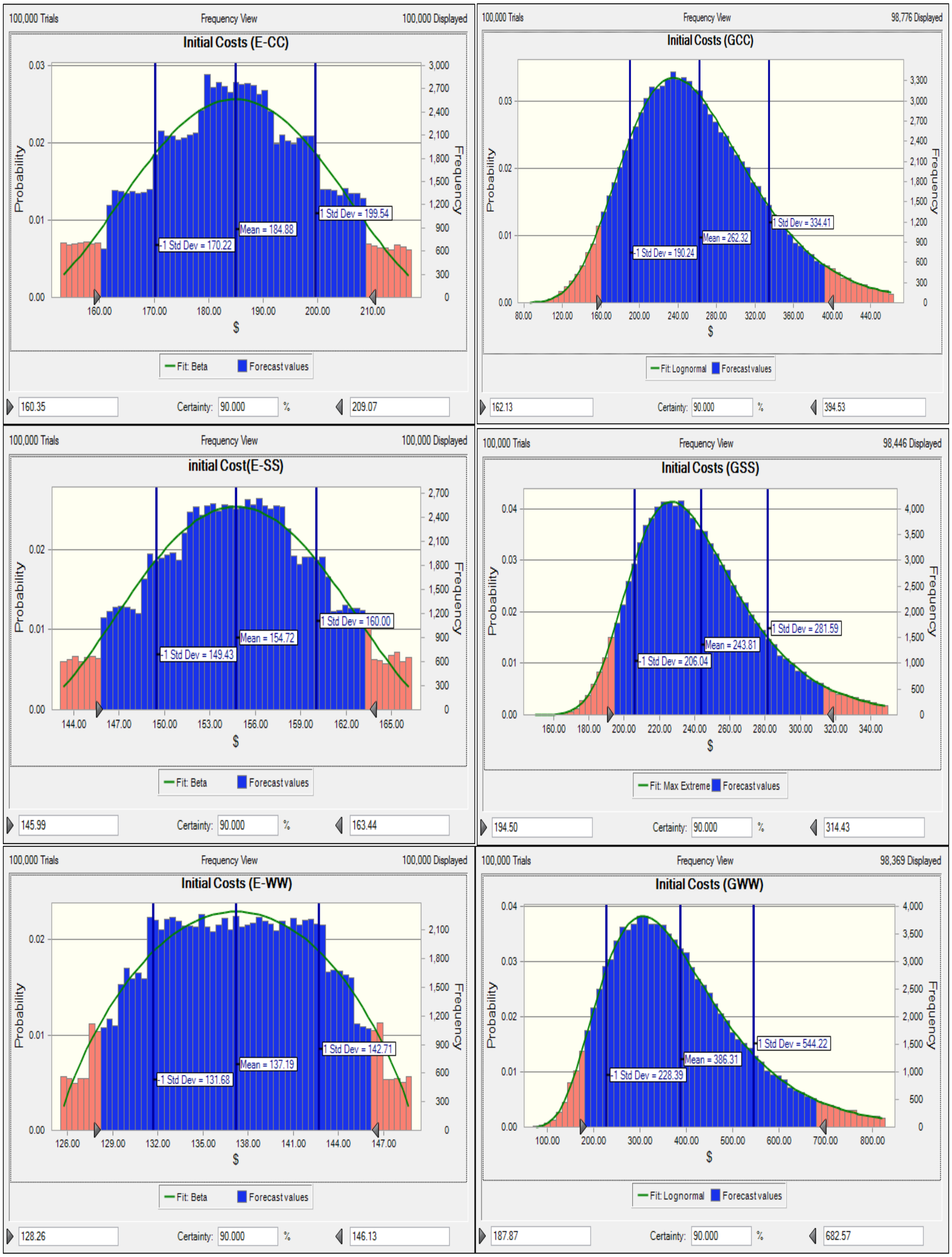


Figure 7.9 The resulted probability distributions of initial costs for various alternatives

Table 7.11 Statistics of the initial costs in ($/ft²) for conventional alternatives

Statistics	CC	CM	SC	SS	SW	WC	WW
Mean	184.96	174.96	161.76	154.71	156.29	142.78	137.15
Median	184.99	174.95	161.68	154.76	156.31	142.68	137.18
Mode	192.82	153.36	144.37	143.3	143.57	127.99	140.9
Standard Deviation	14.85	10.25	8.65	5.26	5.76	8.12	5.55
Variance	220.66	105.13	74.85	27.65	33.2	65.9	30.8
Skewness	-0.006	0.0111	0.0188	-0.0028	-0.005	0.0177	0.0011
Kurtosis	2.33	2.29	2.38	2.32	2.33	2.3	2.07
Coeff. of Variability	0.0803	0.0586	0.0535	0.034	0.0369	0.0569	0.0405
Minimum	152.83	152.83	143.1	143.15	143.47	125.18	125.52
Maximum	217.19	197.47	180.81	166.28	169.03	160.44	148.85
5% percentile	160.31	158.03	147.21	146.05	146.83	129.50	128.11
50% percentile	184.99	174.95	161.68	154.76	156.31	142.68	137.18
70% percentile	193.23	180.74	166.56	157.65	159.48	147.39	140.78
95% percentile	209.48	191.89	176.45	163.32	165.70	156.18	146.16

Table 7.12 Statistics of the initial costs in ($/ft²) for sustainable alternatives

Statistics	GCC	GCM	GSC	GSS	GSW	GWC	GWW
Mean	262.26	240.96	287.75	244.01	297.35	312.44	386.22
Median	252.82	203.82	236.76	237.99	324.87	312.39	357.54
Mode	---	---	---	---	---	---	---
Standard Deviation	72	152.16	163.7	37.94	78.79	136.6	159.34
Variance	5183	23153	26796	1439	6207	18660	25388
Skewness	0.8565	23.76	5.25	1.2	-0.5207	-0.0252	1.31
Kurtosis	4.35	1171.32	49.26	5.76	1.73	4.23	6.21
Coeff. of Variability	0.2745	0.6315	0.5689	0.1555	0.265	0.4372	0.4126
Minimum	85.4	161.53	173.18	160.47	158.36	-420.61	71.69
Maximum	658.44	8974.76	2938.88	550.03	378.45	997.72	1587.74
5% Percentile	161.48	164.53	183.14	194.57	161.68	93.91	185.87
50% Percentile	252.82	203.82	236.75	237.98	324.87	312.37	357.54
70% Percentile	291.90	240.79	287.97	257.01	367.75	377.33	436.70
95% Percentile	391.64	428.10	547.35	315.46	378.42	534.18	681.98

Figures 7.10 and 7.11 present the cumulative probability distributions of initial costs for the conventional and sustainable alternatives, respectively. The output of the simulation shows that all conventional alternatives apparently have lower

initial costs compared to the sustainable alternatives. The pure wood school building (WW) has the minimum cumulative initial cost for all the confidence levels tested (\$137-\$146/ft^2). The next-lowest initial cost option is a wood school building with exterior brick walls (WC), followed by a steel school (SS). The highest initial cost among the conventional alternatives is for precast concrete (CC). A conventional wood school structure will reduce the initial cost by 43%, 37%, and 35% compared to a precast concrete school over the 95%, 70%, and 50% median confidence levels, respectively.

The cumulative distributions of the sustainable alternatives in figure 7.11 indicate inconsistency in the consequences of their performance across the various confidence levels. The minimum initial cost at the 95% percentile confidence level is recorded at \$315/ft^2 for green steel schools (GSS) followed by steel with wood facades (GSW), and then the precast concrete alternative (GCC). At the 70% percentile confidence level, the initial costs are reduced while the level of risk increases to 30%. The minimum cumulative initial cost is \$240/ft^2 for the sustainable concrete alternative with cavity walls (GCM), followed by the sustainable steel alternative (GSS) and then the steel with exterior brick (GSC) option. At the 50% percentile confidence level, the minimum initial cost is recorded at \$203/ft^2 for the concrete alternative with cavity walls (GCM), followed by steel structures with exterior brick (GSC) and then steel with wood facades (GSW). Applying the conventional wood alternative will reduce the initial cost by about 300% compared to the sustainable wood alternative at the 70% percentile confidence level.

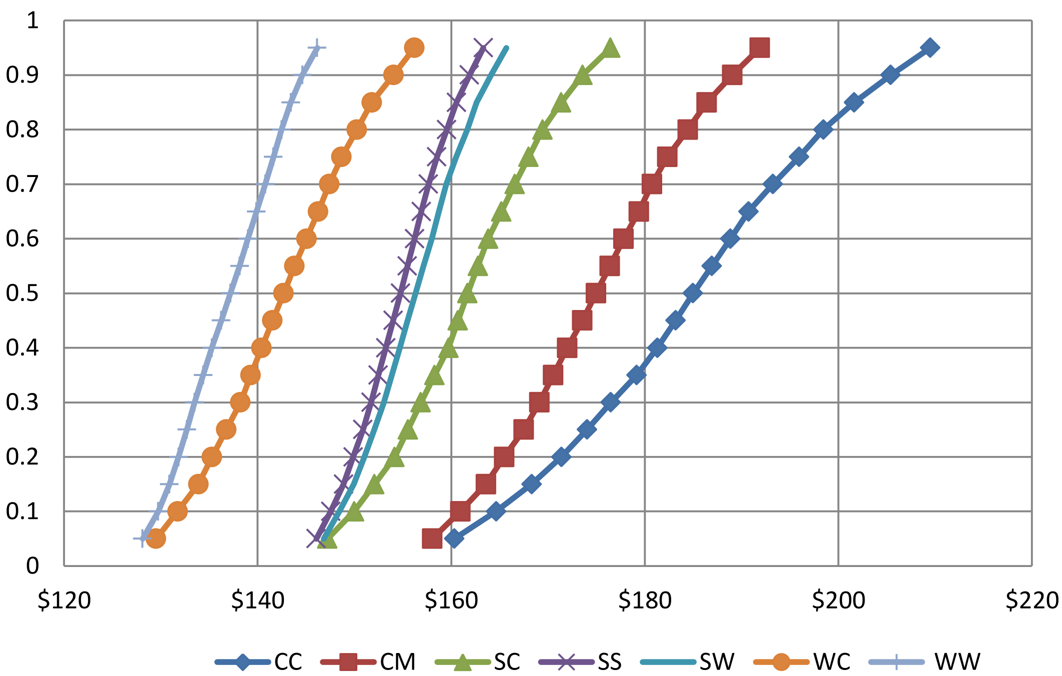


Figure 7.10 Cumulative probability distributions of initial costs for conventional alternatives

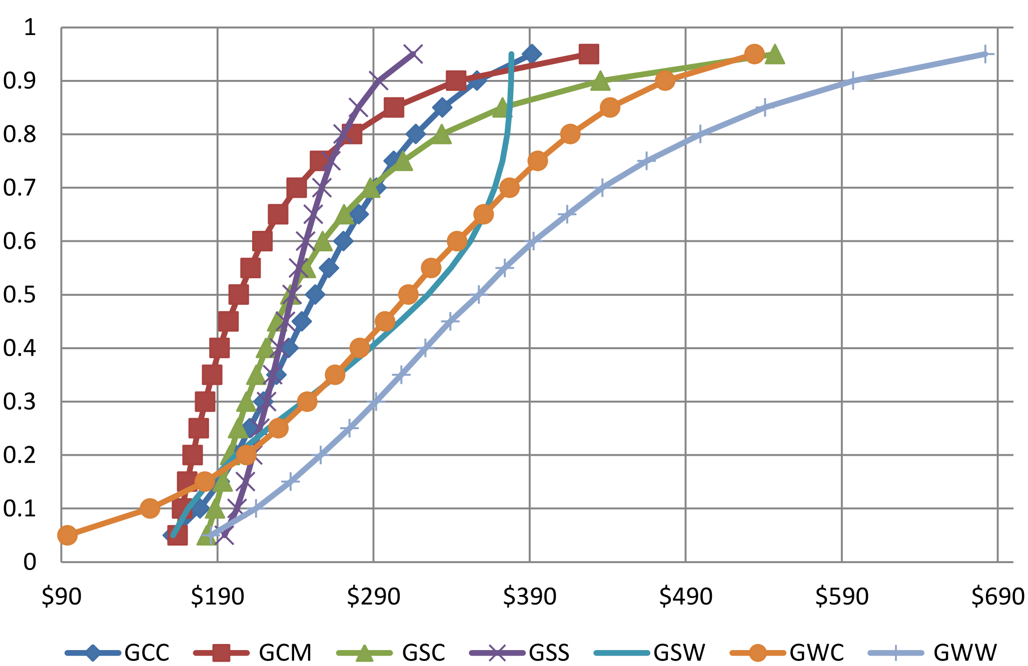


Figure 7.11 Cumulative probability distributions of initial costs for sustainable alternatives

Table 7.13 displays the probable minimum achievable utility scores in initial cost criterion according to the various alternatives'. The result of the selection framework indicates that conventional alternatives apparently can achieve higher utility scores or lower initial costs compared to sustainable alternatives. The first two ranks are occupied by conventional wood alternatives (WW) and (WC) followed by the three steel alternatives (SS), (SW), and (SC). The ranking order of the first seven alternatives is consistent over all the confidence levels. The sustainable alternatives' performances almost are out of the acceptable or preferred utility range at a 95% percentile confidence level. The options ranked in the 8^{th} to 13^{th} positions indicate the variety in the alternatives' performances across each confidence level. For example, the 8^{th} rank is occupied by the green steel alternative (GSS) at the 95% percentile confidence level while that same rank is occupied by the sustainable concrete (GCM) at 70% and 50% percentile.

Table 7.13 Minimum score & ranking of alternatives in IC over confidence levels

Alternatives	95% percentile		70% percentile		50% percentile (Median)	
	Minimum score	Ranking	Minimum score	Ranking	Minimum score	Ranking
CC	15.69	7	18.21	7	19.51	7
CM	18.42	6	20.18	6	21.11	6
SC	20.87	5	22.48	5	23.28	5
SS	23.01	3	23.94	3	24.42	3
SW	22.62	4	23.64	4	24.16	4
WC	24.18	2	25.00	2	25.00	2
WW	25.00	1	25.00	1	25.00	1
GCC	0.00	10	3.96	11	9.31	12
GCM	0.00	11	11.04	8	16.56	8
GSC	0.00	13	4.48	10	11.63	9
GSS	0.92	8	8.72	9	11.45	10
GSW	0.00	9	0.00	12	0.00	13
GWC	0.00	12	0.00	13	1.31	11
GWW	0.00	14	0.00	14	0.00	14

7.5.2 Running Costs (RC)

Figure 7.12 shows the regression sensitivity graph of the present values of the running costs for the precast concrete alternative. The regression sensitivity shows that a major repairs cost has largest positive correlation influence on the PV of running costs, with a value of 53.5%. The next-significant factor is the discount rate, which has a negative 26.2% correlation with running costs. Other parameters such as operating and maintenance costs, energy costs, and inflation rate have a positive correlation with values of 7.3%, 7%, and 5.4%, respectively.

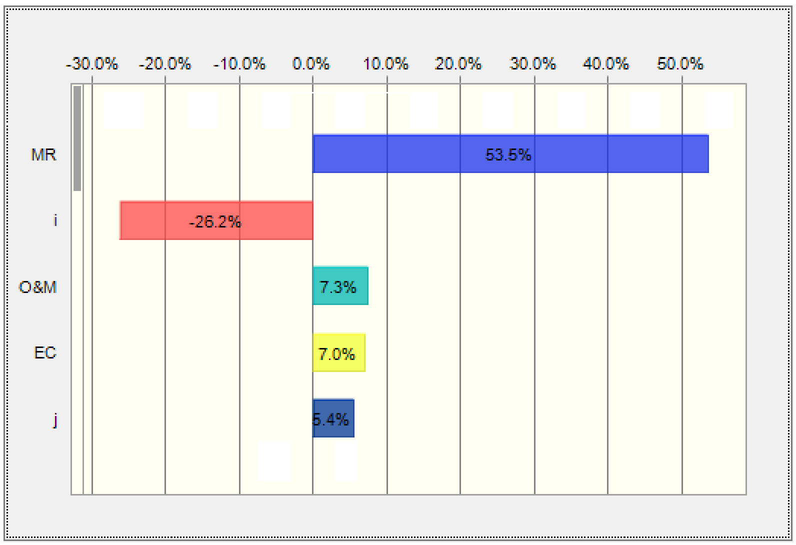


Figure 7.12 Regression sensitivity analysis of present value with the RC

Figure 7.13 presents the probability distribution for three conventional and sustainable alternatives. The Beta PERT probability distribution is the best fit for the running costs of sustainable school buildings. The following probability functions can be the best fit of the running costs of conventional alternatives: Lognormal and Max Extreme probability functions. The running cost statistics for conventional and sustainable alternatives are displayed in Tables 7.14 and 7.15.

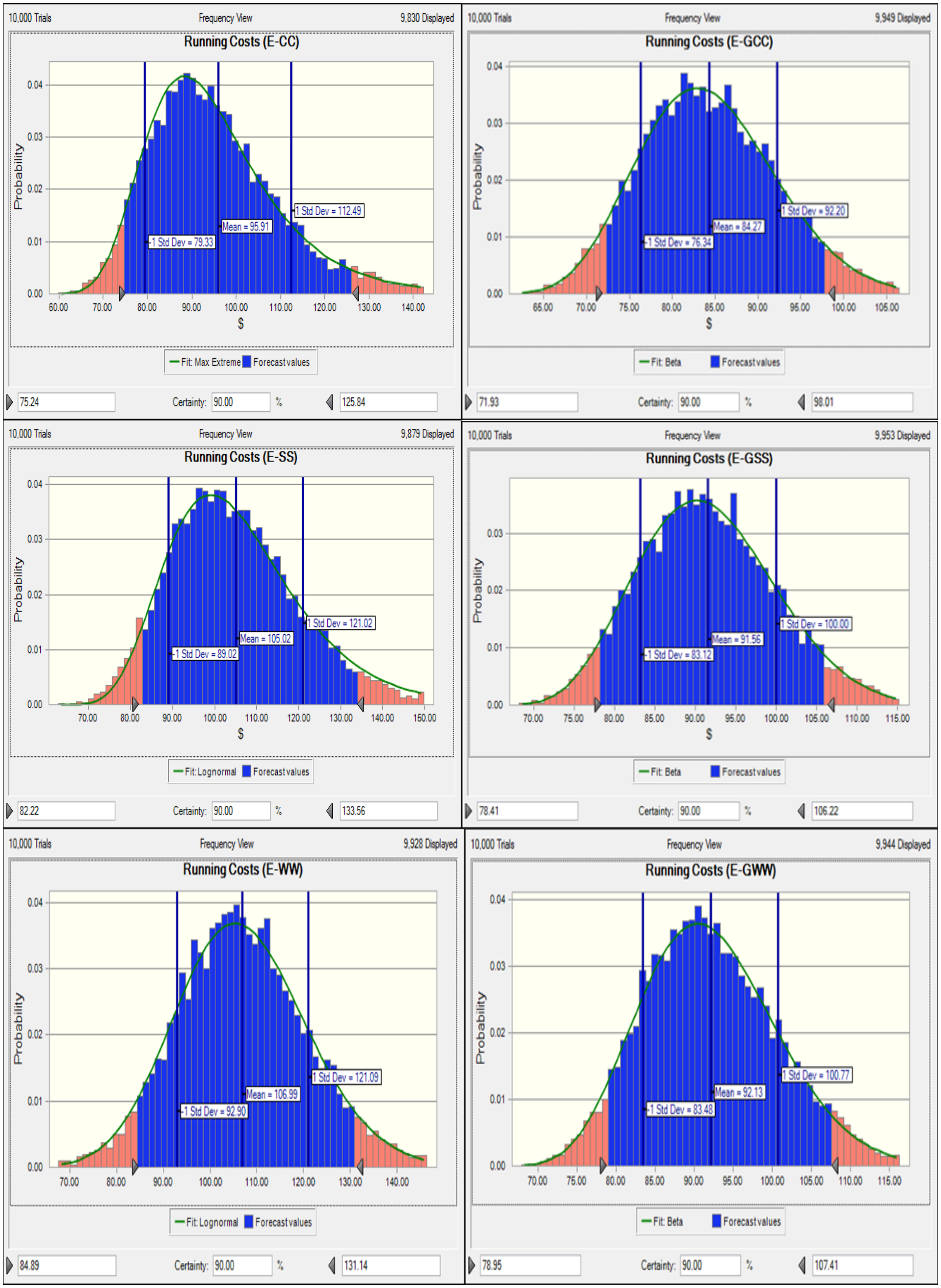


Figure 7.13 The resulted probability distributions of the running costs of various alternatives

The minimum mean value is recorded for sustainable precast concrete schools (GCC) at \$84.3 /ft^2, while the maximum value is \$106.9 /ft^2 for conventional wood schools with exterior brick (GWC).

Table 7.14 Statistics of the PV of RC for conventional alternatives (in \$/ft²)

Statistics	CC	CM	SC	SS	SW	WC	WW
Mean	95.90	96.17	104.62	104.80	104.10	106.91	106.82
Median	93.29	93.41	102.70	103.04	102.45	106.41	106.07
Mode	---	---	---	---	---	---	---
Standard Deviation	16.88	16.51	15.83	15.81	15.72	14.24	13.94
Variance	285.04	272.53	250.59	249.96	247.15	202.79	194.28
Skewness	1.93	1.75	0.7864	0.7559	0.7480	0.2230	0.3180
Kurtosis	13.18	10.91	4.22	4.06	4.18	3.40	3.27
Coeff. of Variability	0.1761	0.1717	0.1513	0.1509	0.1510	0.1332	0.1305
Minimum	57.71	59.13	63.02	64.25	62.97	43.72	61.77
Maximum	322.30	308.93	199.91	188.80	198.00	174.55	176.76
5% Percentile	74.88	75.58	82.23	82.31	81.71	84.60	85.14
50% Percentile	93.29	93.41	102.69	103.04	102.45	106.41	106.07
70% Percentile	100.94	101.24	111.21	111.23	110.70	113.72	113.22
95% Percentile	125.62	125.24	133.10	133.42	132.71	130.93	130.98

Table 7.15 Statistics of the PV of the RC for sustainable alternatives (in \$/ft²)

Statistics	GCC	GCM	GSC	GSS	GSW	GWC	GWW
Mean	84.32	86.07	91.75	91.78	86.19	95.65	92.16
Median	83.78	85.62	91.26	91.35	85.94	95.28	91.74
Mode	---	---	---	---	---	---	---
Standard Deviation	7.84	7.87	8.07	8.54	9.78	8.26	8.68
Variance	61.44	61.92	65.16	72.87	95.64	68.28	75.33
Skewness	0.31	0.27	0.28	0.28	0.15	0.25	0.26
Kurtosis	2.97	2.80	2.78	2.83	2.91	2.80	2.95
Coeff. of Variability	0.09	0.09	0.09	0.09	0.11	0.09	0.09
Minimum	62.08	64.07	69.28	65.85	54.55	73.15	61.60
Maximum	116.34	114.94	120.33	122.36	127.40	125.36	136.34
5% Percentile	72.16	73.77	79.24	78.65	70.53	82.71	78.74
50% Percentile	83.78	85.62	91.26	91.35	85.94	95.28	91.73
70% Percentile	88.22	90.02	95.78	96.02	91.16	99.78	96.49
95% Percentile	98.07	99.68	105.94	106.68	102.66	110.06	106.97

Figures 7.14 and 7.15 summarize the cumulative probability distributions of running costs for conventional and sustainable alternatives, respectively. The simulation shows that every sustainable alternative apparently has lower running costs than any of conventional alternatives. Green precast concrete school buildings (GCC) have the minimum cumulative running costs over all the confidence levels (\$83.8-\$98/ft^2). The highest running cost among the sustainable alternatives is for steel structures (GSS). Building a green precast concrete school will reduce the running cost by 35%, 28%, and 26% compared to a conventional wood school, according to the 95%, 70%, and 50% median confidence levels, respectively.

The cumulative distributions of conventional alternatives in Figure 7.14 indicate that structure type has a significant correlation with running costs. The lowest running cost is recorded for conventional concrete structures followed by steel structures and then wood. Among the sustainable alternatives, the minimum running cost at the 95% confidence level is \$98/ft^2 for green precast concrete (GCC), followed by concrete with masonry walls (GCM) and then steel with wood facades (GSW). At the 70^{th} percentile confidence level, the minimum cumulative running cost is close to \$88.2/ft^2 for sustainable precast concrete (GCC), followed by (GCM) and then steel with exterior wood (GSW). At the 50^{th} percentile confidence level, the minimum initial cost is \$83.2/ft^2 for the concrete alternative (GCC). At the 70th percentile confidence level, applying the conventional precast concrete alternative will reduce the running costs by about 13% compared to the conventional wood alternative.

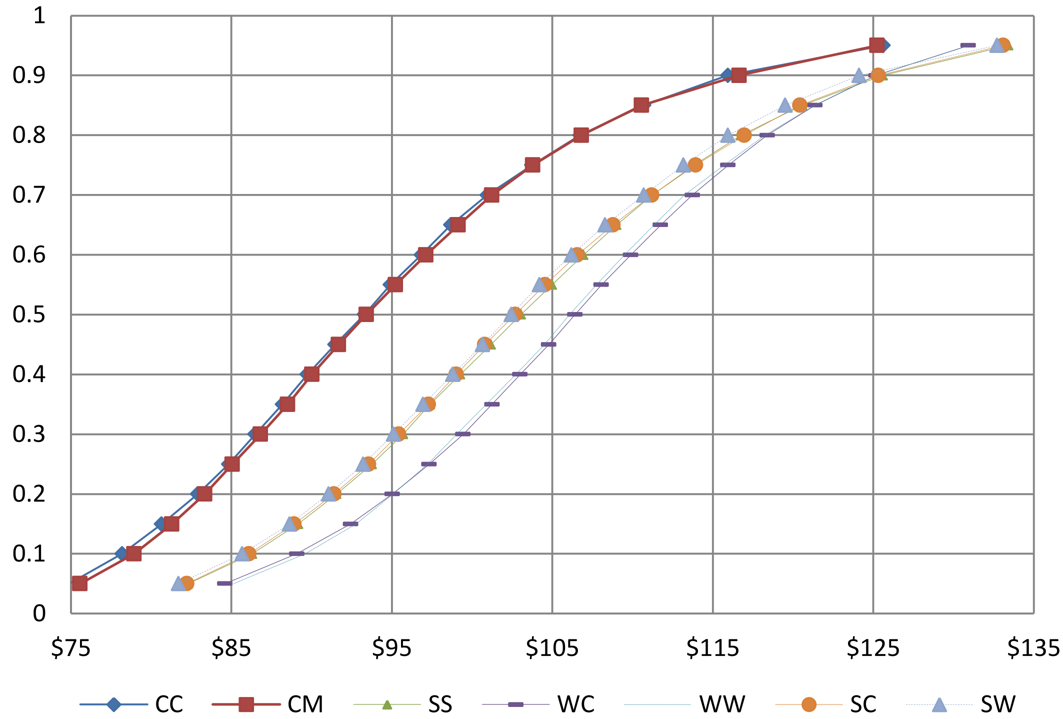


Figure 7.14 Cumulative probability distributions of running costs for conventional alternatives

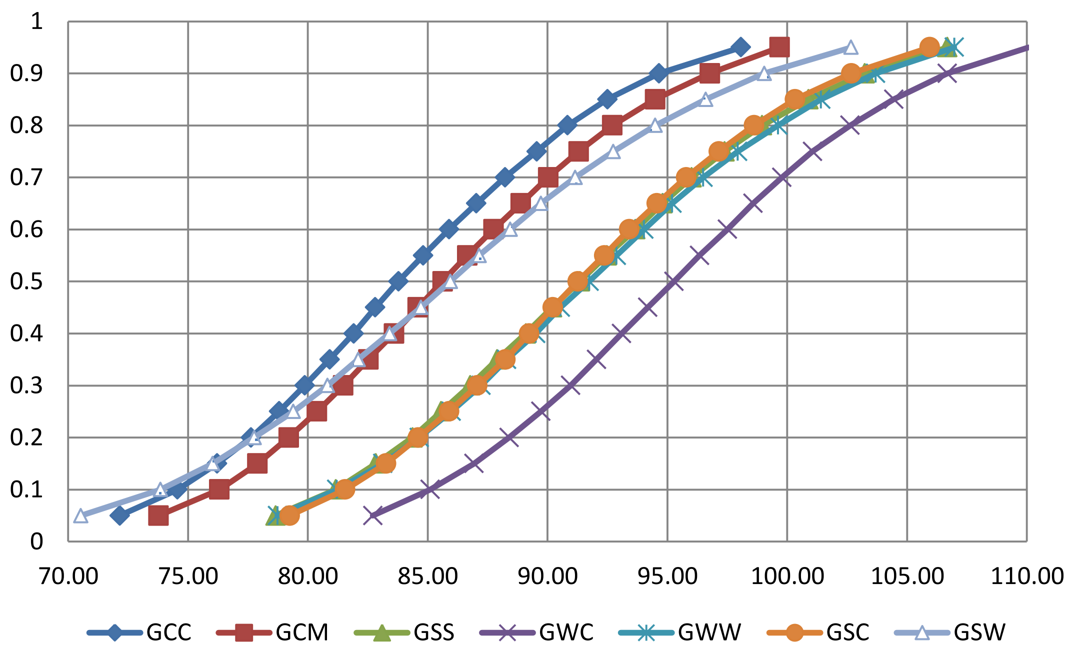


Figure 7.15 Cumulative probability distributions of running costs for sustainable alternatives

Table 7.16 presents the probable minimum achievable utility scores in for running costs according to the various alternatives over the three tested confidence levels. The result of the selection framework indicates that sustainable alternatives apparently achieved higher utility scores due to their lower running costs. The first two ranks are occupied by sustainable concrete alternatives, GCC and GCM, followed by the two sustainable wood alternatives GWW and GWC. The 5th and 6th ranks are occupied by green steel alternatives GSC and GSW, respectively. The 7th to the 14th ranks show the variety of the performances of alternatives at the different confidence levels. The conventional precast concrete alternative is ranked 9th, 8th, and 7th with minimum utility scores of 0.02, 18.5 and 23.3 over the various confidence levels. The minimum utility scores earned by the different alternatives range between 0.0 – 20.4, 9.48 – 26.3, and 14.8 – 28.7 over the three confidence levels (95, 70 and 50%).

Table 7.16 Minimum score & alternatives ranking in RC at the confidence levels

Alternatives	95% percentile		70% percentile		50% percentile (Median)	
	Minimum score	Ranking	Minimum score	Ranking	Minimum score	Ranking
CC	0.02	9	18.56	8	23.39	7
CM	0.21	8	18.36	9	23.32	8
SC	0.00	14	11.35	12	17.16	12
SS	0.00	10	9.48	14	14.83	14
SW	0.00	11	9.86	13	15.07	13
WC	0.00	13	11.37	11	17.39	11
WW	0.00	12	11.74	10	17.56	10
GCC	20.43	1	26.34	1	28.75	1
GCM	19.39	2	25.31	2	27.77	2
GSC	14.64	5	21.72	5	24.54	5
GSS	12.21	7	19.32	7	22.18	9
GSW	14.44	6	21.43	6	24.32	6
GWC	15.16	4	21.87	4	24.59	4
GWW	17.41	3	24.65	3	27.60	3

7.5.3 Environmental Impact Costs (EIC)

Figure 7.16 shows the regression sensitivity graph of the environmental impact for the green precast concrete alternative. Since EIC are a future cost, the regression sensitivity analysis showed that the discount rate has significant negative correlation effects on the present value of environmental costs, with a value of 62.8%. The expected uncertainty in the EIC value has a 37.1%.positive correlation to the PV of EICs

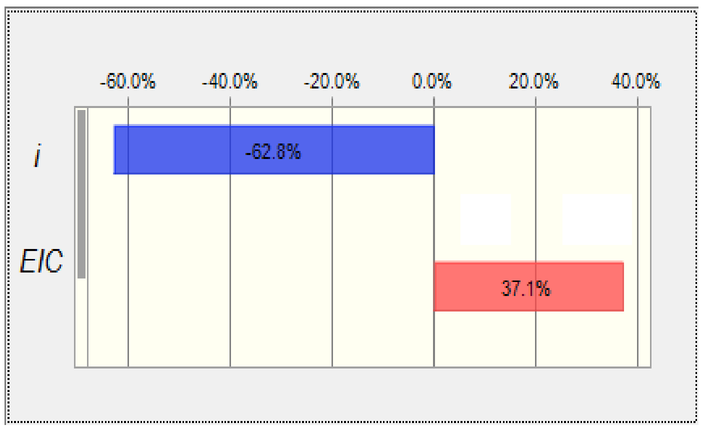


Figure 7.16 Regression sensitivity analysis of the present value of EI costs

Figure 7.17 presents the probability distribution of the environmental impact costs for three conventional and sustainable alternatives. Beta probability distribution is the best fit of the environmental impact costs for conventional school buildings, while the Lognormal probability distribution is the best fit for sustainable alternatives, as indicated in Figure 7.17. The statistical breakdown of the PVs of the environmental impact costs for conventional and sustainable alternatives are summarized in Tables 7.17 and 7.18, respectively. The minimum mean value of EIC is recorded for sustainable steel structures with wood facades (GSW) at \$0.52 /ft^2, while the maximum mean value is \$1.05 /ft^2 for steel alternative (SS).

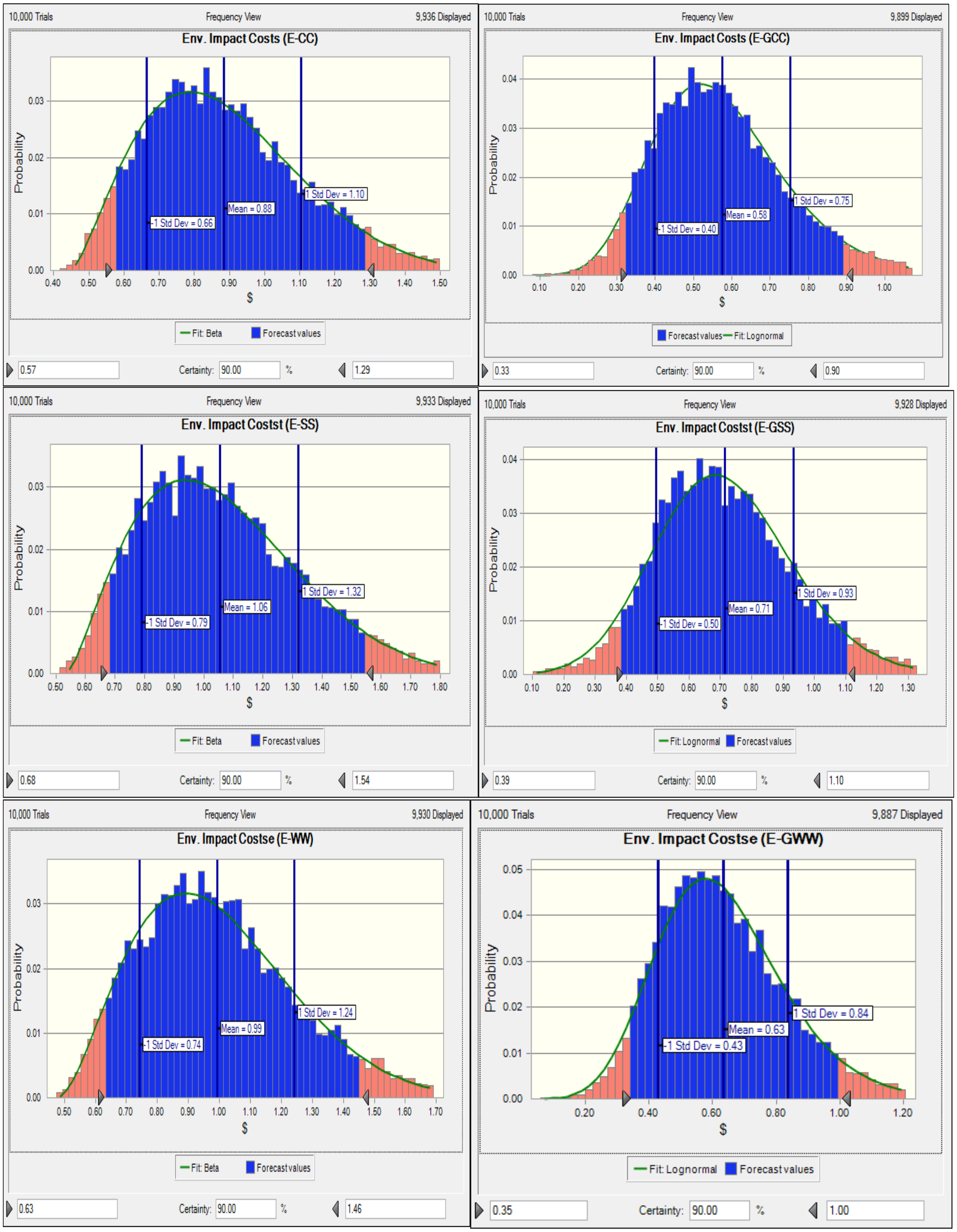


Figure 7.17 The resulted probability distributions of the environmental impact costs of various alternatives

Table 7.17 Statistical breakdown of the PVs of environmental impact costs in $/ft²
for conventional alternatives

Statistics	CC	CM	SC	SS	SW	WC	WW
Mean	0.892	1.006	1.032	1.050	0.979	0.964	0.994
Median	0.868	0.973	0.999	1.020	0.947	0.932	0.962
Mode	---	---	---	---	---	---	---
Standard Deviation	0.219	0.252	0.259	0.260	0.244	0.241	0.248
Variance	0.048	0.063	0.067	0.068	0.060	0.058	0.061
Skewness	0.556	0.607	0.585	0.611	0.541	0.589	0.577
Kurtosis	2.975	3.014	2.989	3.093	2.872	2.987	2.974
Coeff. of Variability	0.246	0.251	0.251	0.248	0.250	0.250	0.249
Minimum	0.418	0.467	0.489	0.510	0.454	0.448	0.487
Maximum	1.707	1.962	2.015	2.077	1.882	1.925	1.906
5% Percentile	0.57	0.65	0.67	0.68	0.63	0.62	0.64
50% Percentile	0.87	0.97	1.00	1.02	0.95	0.93	0.96
70% Percentile	0.99	1.12	1.15	1.16	1.09	1.07	1.10
95% Percentile	1.30	1.47	1.51	1.54	1.43	1.42	1.45

Table 7.18 Statistical breakdown of the PVs of environmental impact costs in $/ft²
for sustainable alternatives

Statistics	GCC	GCM	GSC	GSS	GSW	GWC	GWW
Mean	0.57	0.70	0.71	0.72	0.52	0.71	0.64
Median	0.55	0.67	0.68	0.70	0.50	0.68	0.61
Mode	---	---	---	---	---	---	---
Standard Deviation	0.18	0.20	0.19	0.22	0.25	0.18	0.20
Variance	0.03	0.04	0.03	0.05	0.06	0.03	0.04
Skewness	0.7326	0.6504	0.7793	0.3947	0.3649	0.6047	0.7057
Kurtosis	4.03	3.27	3.70	3.19	3.40	3.14	3.91
Coeff. of Variability	0.3075	0.2914	0.2639	0.2998	0.4884	0.2617	0.3190
Minimum	0.04	0.26	0.32	-0.13	-0.34	0.29	-0.08
Maximum	1.59	1.55	1.59	1.58	1.67	1.45	1.72
5% Percentile	0.32	0.41	0.45	0.40	0.13	0.45	0.35
50% Percentile	0.55	0.67	0.68	0.70	0.50	0.68	0.61
70% Percentile	0.64	0.79	0.78	0.82	0.64	0.79	0.72
95% Percentile	0.89	1.08	1.05	1.10	0.96	1.04	1.00

Figures 7.18 and 7.19 summarize the cumulative probability distributions of the environmental impact costs for conventional and sustainable alternatives,

respectively. The output of the simulation shows that all sustainable alternatives apparently have lower EI costs compared conventional alternatives. Green precast concrete school buildings (GCC) have the minimum cumulative running costs at the 95th percentile confidence level with 0.89/ft^2, followed by green steel with wood facades (GSW). These two alternatives have equivalent cost values ($0.63/ft^2) at the 70% confidence level. The green steel alternative, (GSW) lower EIC by about 10% compared to the green precast concrete alternative (GCC) at the median confidence level. The highest EI cost among the sustainable alternatives is for the steel option, GSS. Building a green precast concrete school will reduce the EI costs by 23%, 28%, and 27% over the 95%, 70%, and 50% median confidence levels, respectively, compared to a sustainable steel school (GSS). It is also will reduce the EI costs by 73%, 81%, and 91%, respectively, compared to those attributable to a conventional steel school,(SS) over the three confidence levels .

The cumulative distributions of the conventional alternatives shown in figure 7.18 indicate that structure and envelope types have significant correlation with EI costs. This figure also shows that there is consistency in the consequences of conventional alternatives' performances across the various confidence levels. The lowest EI cost is recorded for conventional precast concrete structures followed by wood and then steel structures. The minimum EIC for conventional alternatives ranges from ($0.87-$1.30/ft^2) for precast concrete alternative while the maximum is ranged between $1.02 to $1.54/ft^2 for the steel alternative over the various tested confidence levels.

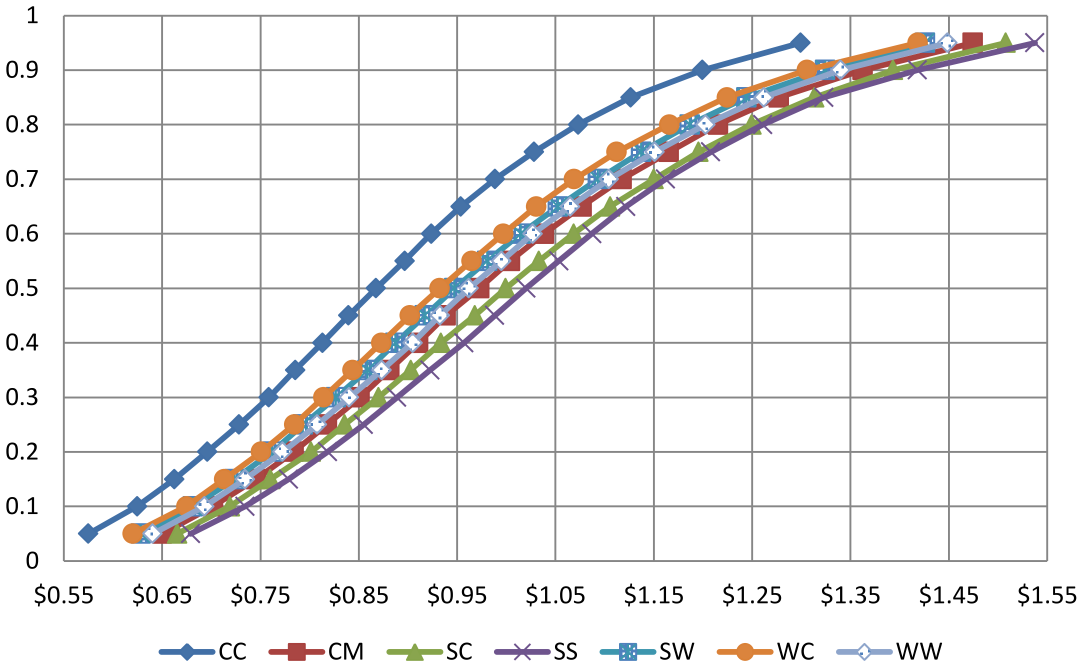


Figure 7.18 Cumulative probability distributions of the environmental impact costs for conventional alternatives

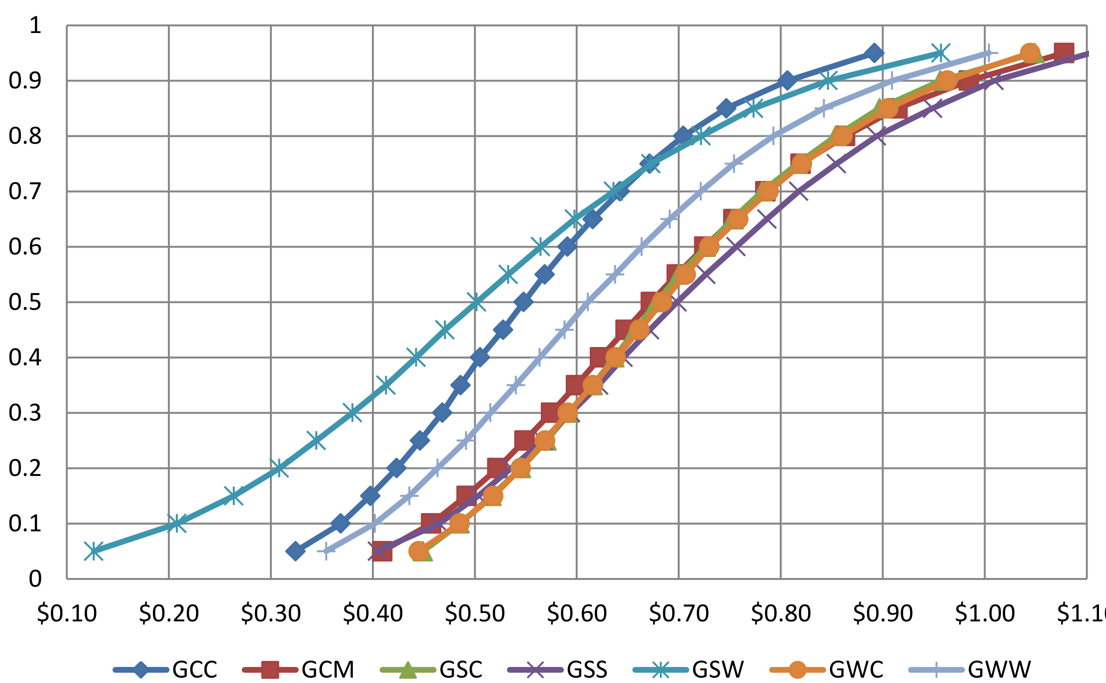


Figure 7.19 Cumulative probability distributions of the environmental impact costs for sustainable alternatives

Table 7.19 presents the probable minimum utility scores achievable by the various alternatives over all the tested confidence levels, in terms of environmental impact costs' criterion. The results of the selection framework indicate that sustainable alternatives apparently achieved higher utility scores due to their lower EICs compared to conventional alternatives. The first two ranks are occupied alternately by sustainable precast concrete (GCC) and green steel with exterior wood (GSW), followed by the green wood alternative (GWW). Consistency is observed in the conventional alternatives' ranks through the various confidence levels. Conventional alternatives could not achieve any score in at the 95% confidence level, which indicates that they are out of the preferred range of the experts. The minimum utility score achieved by all of the alternatives ranged between 0.0 – 3.79, 0.05 – 7.33, and 1.98 – 9.34 for 95th, 70th and 50th percentile confidence levels, respectively.

Table 7.19 Minimum score & ranking of alternatives in EICs over the three tested confidence levels

Alternatives	95% percentile		70% percentile		50% percentile (Median)	
	Minimum score	Ranking	Minimum score	Ranking	Minimum score	Ranking
CC	0.00	8	2.40	8	4.07	8
CM	0.00	12	0.60	12	2.67	12
SC	0.00	13	0.19	13	2.26	13
SS	0.00	14	0.05	14	1.98	14
SW	0.00	10	1.01	10	2.95	10
WC	0.00	9	1.29	9	3.23	9
WW	0.00	11	0.88	11	2.81	11
GCC	3.79	1	7.33	1	8.62	2
GCM	1.15	6	5.20	5	6.90	4
GSC	1.57	5	5.34	4	6.76	5
GSS	0.88	7	4.77	7	6.47	7
GSW	2.81	2	7.33	2	9.34	1
GWC	1.70	4	5.20	6	6.76	6
GWW	2.26	3	6.19	3	7.76	3

7.5.4 Salvage Value (SV)

Figure 7.20 displays the regression sensitivity graph of the salvage value for conventional wood alternatives. Since the salvage value is a future value of a building, the regression sensitivity analysis showed that the discount rate has significant negative correlation effects on the present value of the salvage value, with value of 54.5%. The second major impact is due to the depreciation percentage value, which has 42.2% positive correlation to the PV of the salvage value. Since that salvage value is correlated to initial costs, a school's area has a negative slight correlation of 2.3% and the number of floors has a minor positive correlation of 0.7%

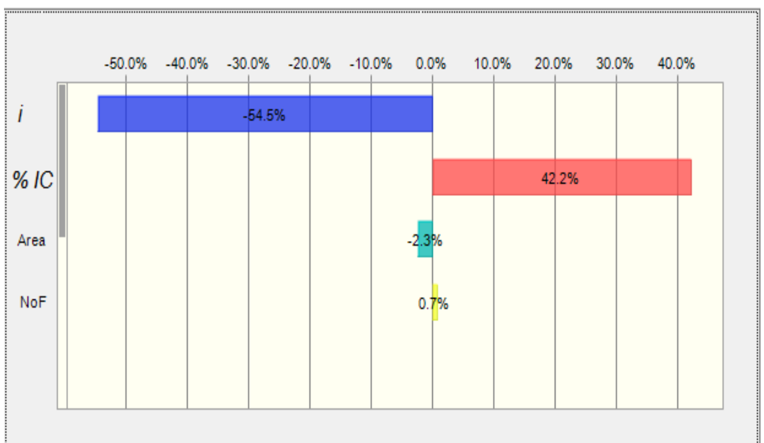


Figure 7.20 Regression sensitivity analysis of the present value of the SV

Figure 7.21 presents the probability distribution of salvage value for three conventional and sustainable alternatives. Beta and normal probability distributions are the best fit for the PV of the salvage value for conventional school buildings, while the Lognormal, Beta and Max Extreme probability distributions are the best fit for sustainable alternatives, as shown in Figure 7.21.

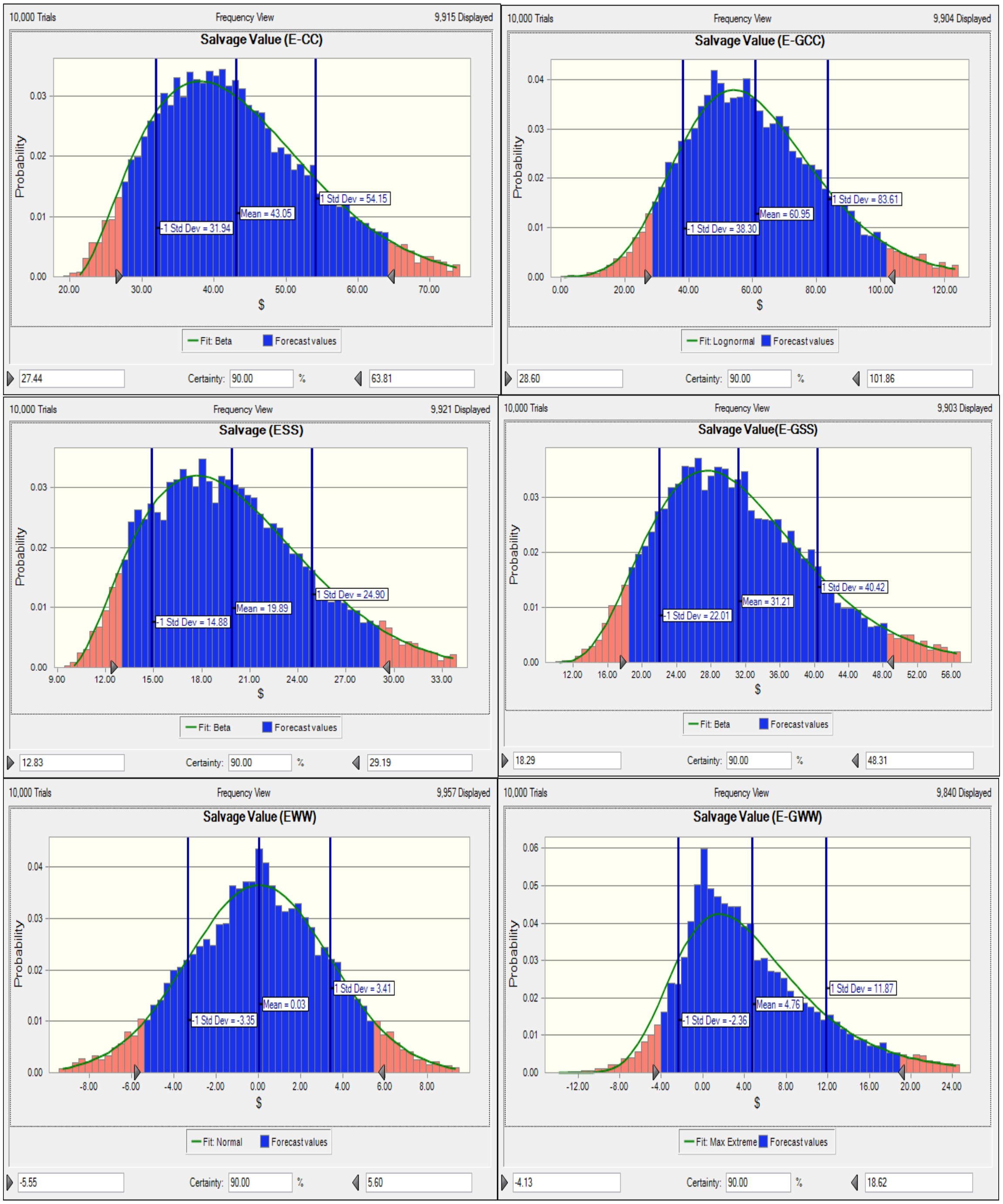


Figure 7.21 The probability distributions of the salvage values of various alternatives

The statistical breakdown of the PV of the salvage value for conventional and sustainable alternatives are summarized in Tables 7.20 and 7.21.The maximum mean of the PV of a salvage value is recorded for sustainable precast concrete structures (GCC) at \$60.38/ft^2, while the minimum mean value is \$0.05 /ft^2 for a conventional pure wood school (WW), as shown in Table 7.20.

Table 7.20 Statistical details of the PV of the salvage values in \$/ft² for conventional alternatives

Statistics	CC	CM	SC	SS	SW	WC	WW
Mean	42.74	37.44	26.98	19.84	20.03	11.08	0.05
Median	41.35	36.38	26.13	19.23	19.35	10.57	0.03
Mode	---	---	---	---	---	---	---
Standard Deviation	11.01	9.23	6.72	5.09	5.11	3.55	3.37
Variance	121.20	85.15	45.12	25.95	26.10	12.58	11.34
Skewness	0.6499	0.5596	0.5884	0.6222	0.6162	0.7143	0.0189
Kurtosis	3.22	2.95	3.03	3.13	3.06	3.49	2.94
Coeff. of Variability	0.2576	0.2465	0.2489	0.2567	0.2551	0.3202	62.76
Minimum	19.32	16.91	11.97	9.43	9.26	3.40	-11.40
Maximum	91.39	74.45	53.66	41.08	39.56	27.64	11.69
5% Percentile	63.28	54.77	39.47	29.43	29.75	17.76	5.56
50% Percentile	41.35	36.38	26.13	19.23	19.34	10.57	0.03
70% Percentile	35.90	31.79	22.83	16.71	16.89	8.93	-1.67
95% Percentile	27.17	24.21	17.42	12.58	12.82	6.10	-5.54

Table 7.21 Statistical detail of the PV of the salvage values in \$/ft² for sustainable alternatives

Statistics	GCC	GCM	GSC	GSS	GSW	GWC	GWW
Mean	60.38	49.72	45.64	31.36	38.16	24.54	5.00
Median	57.89	47.63	43.47	30.14	36.26	22.75	3.33
Mode	---	---	---	---	---	---	---
Standard Deviation	22.56	19.05	18.99	9.31	14.48	12.43	7.39
Variance	508.89	362.93	360.48	86.74	209.81	154.56	54.68
Skewness	0.6620	0.6436	0.6592	0.7059	0.7515	0.8950	1.17
Kurtosis	3.63	3.58	3.80	3.45	3.93	4.59	5.12
Coeff. of Variability	0.3736	0.3832	0.4160	0.2970	0.3796	0.5066	1.48
Minimum	-4.86	-0.02	-16.23	10.22	-0.34	-18.61	-17.93
Maximum	170.11	141.90	140.32	72.92	128.76	115.92	52.35
5% Percentile	101.21	84.96	80.23	48.63	64.37	47.55	19.36
50% Percentile	57.89	47.61	43.47	30.14	36.26	22.75	3.33
70% Percentile	47.16	38.45	34.85	25.70	29.60	17.16	0.53
95% Percentile	28.09	22.48	18.33	18.39	17.45	7.49	-4.13

Figures 7.22 and 7.23 summarize the cumulative probability distributions of the salvage values for conventional and sustainable alternatives, respectively. The simulation shows that the salvage values are significantly affected by the structure and envelope types. It also indicates that sustainable alternatives have higher salvage values compared to conventional ones with the same structure and envelope type. Both graphs indicate that the performances of conventional and sustainable alternatives are consistent throughout the various confidence levels. Green precast concrete school buildings (GCC) have the maximum cumulative salvage value at \$28.1, \$47.1, and \$57.9/ft^2 at the 95%, 70%, and 50% confidence levels. The salvage value of the (GCC) alternative increases by close to 68% and 106% when comparing the results of the 95% level to those of the 70% and 50% confidence levels, respectively. The second-highest salvage value is recorded at \$27.1/ft^2 for the conventional precast concrete alternative (CC), followed by conventional concrete with masonry walls (CM) at the 95% confidence level.

The cumulative distributions of conventional alternatives in figure 7.22 indicate that concrete buildings have the highest salvage value followed by steel buildings and then by wood alternatives. The minimum salvage values of conventional alternatives range from \$-5.54 - \$5.56/ft^2 for a wood alternative (WW) to the maximum values that are between \$27.2 and \$63.3/ft^2, for precast concrete schools, over all the various confidence levels.

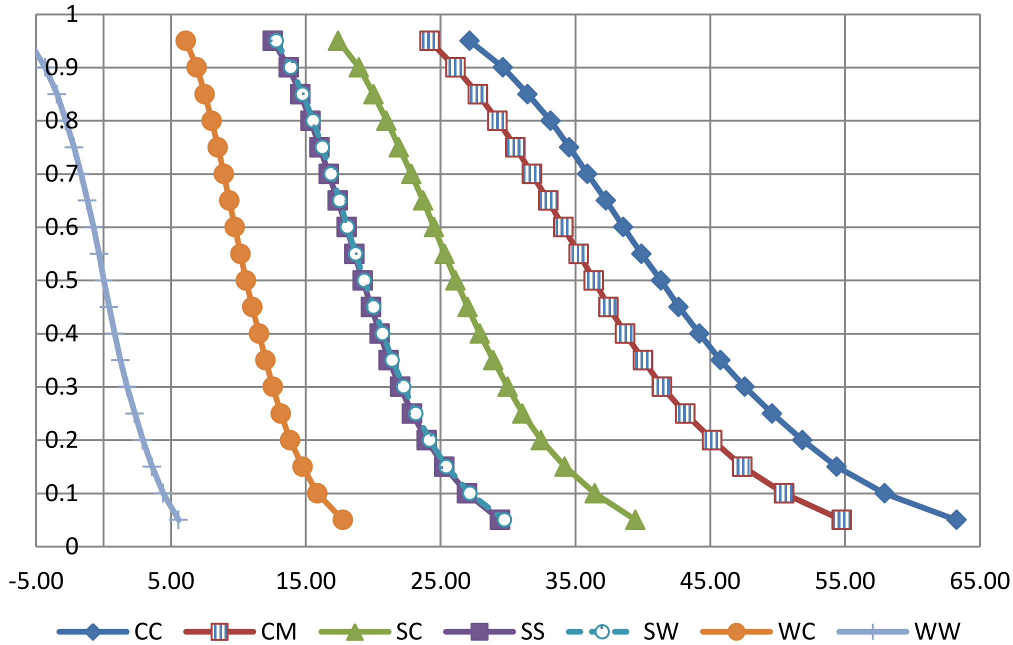


Figure 7.22 Cumulative probability distributions of salvage values for conventional alternatives

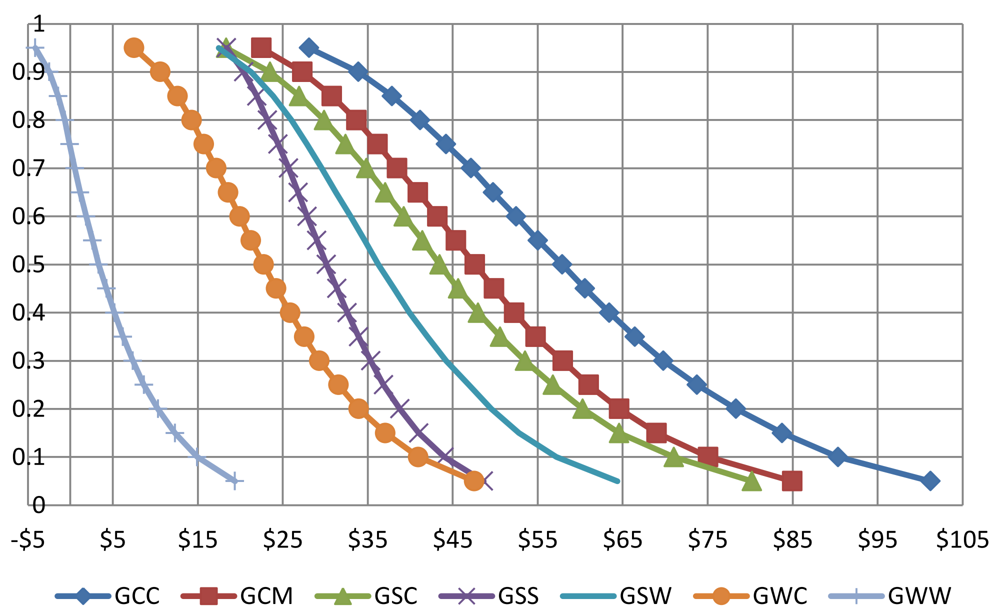


Figure 7.23 Cumulative probability distributions of salvage values for sustainable alternatives

Table 7.22 presents the probable minimum achievable utility scores for the salvage value criterion according to the various alternatives over all the tested confidence levels. The result of the selection framework indicates that sustainable alternatives apparently achieved higher utility scores due to their high initial costs. The first rank is occupied by sustainable precast concrete alternatives (GCC), with utility scores of 3.2, 6.15, and 7.7 out of 10 at 95%, 70%, and 50% percentile confidence levels. A green concrete alternative (GCM) is upgraded from the 4th rank at the 95th percentile to be in the 2nd rank in the 70 and 50th percentiles with an increase of 100% and 160% in its utility score, respectively. The minimum utility score achieved ranged between 0.0 – 3.27, 0.0 – 6.15 and 0.0 – 7.77 over the various confidence levels.

Table 7.22 Minimum score obtained in salvage value & ranking of alternatives over the three confidence levels

Alternatives	95% percentile		70% percentile		50% percentile (Median)	
	Minimum score	Ranking	Minimum score	Ranking	Minimum score	Rankin g
CC	3.139	2	4.457	3	5.280	4
CM	2.692	3	3.836	5	4.529	5
SC	1.666	8	2.483	8	2.982	8
SS	0.936	10	1.559	11	1.940	11
SW	0.972	9	1.586	10	1.956	10
WC	0	12	0.384	12	0.632	12
WW	0	14	0	14	0	14
GCC	3.278	1	6.157	1	7.777	1
GCM	2.430	4	4.842	2	6.225	2
GSC	1.804	6	4.298	4	5.600	3
GSS	1.813	5	2.917	7	3.587	7
GSW	1.671	7	3.506	6	4.511	6
GWC	0.167	11	1.627	9	2.471	9
GWW	0	13	0	13	0	13

7.5.5 Sustainability (LEED Score)

Figure 7.24 displays the probability distribution of the LEED's scores most likely to be achieved for a set of six conventional and sustainable alternatives.

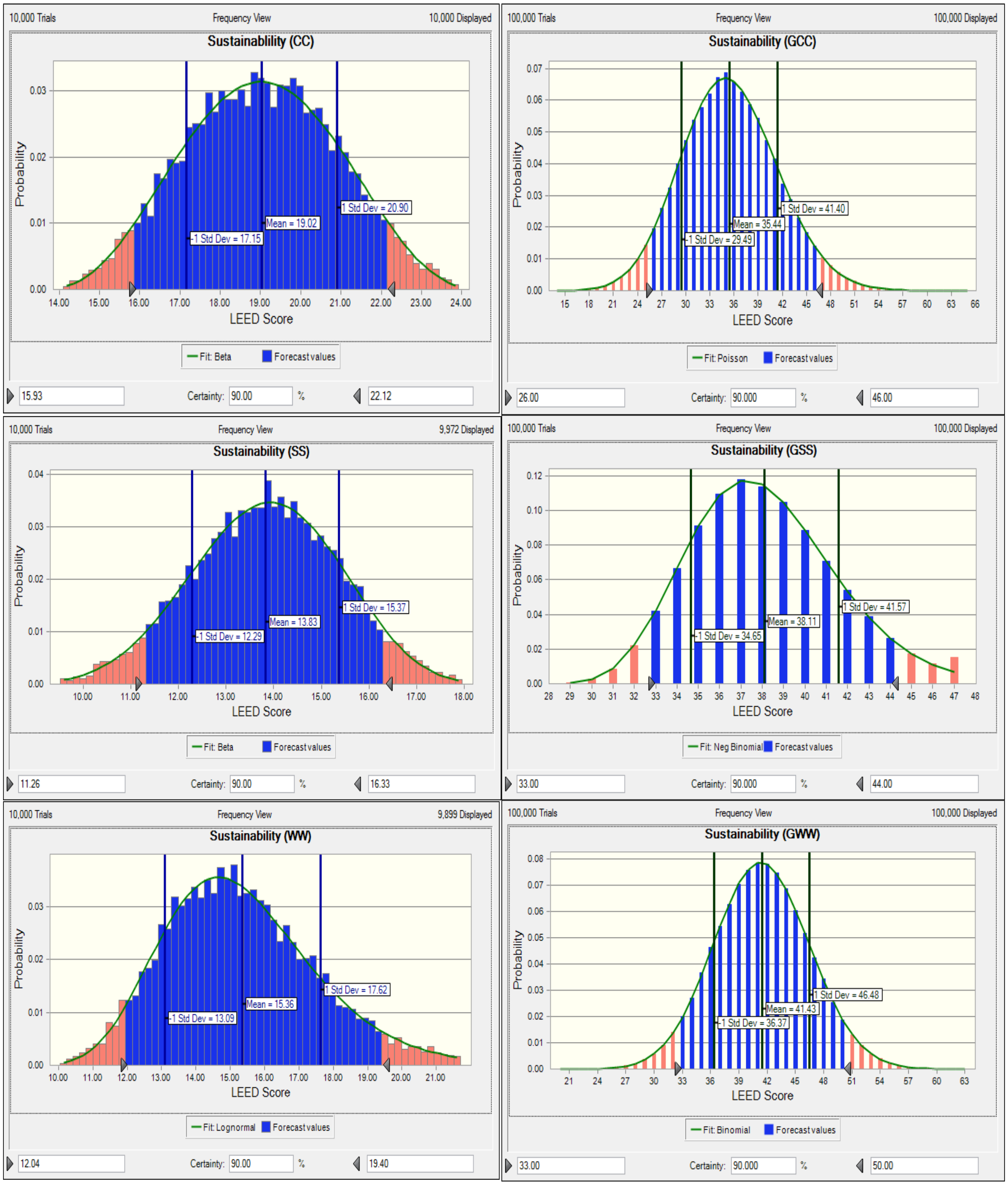


Figure 7.24 The resulted probability distributions of sustainability LEED scores) of various alternatives

The detailed statistics of the LEED scores obtained for conventional and sustainable alternatives are summarized in tables 7.23 and 7.24 respectively.

Table 7.23 Statistics of the LEED scores obtained by conventional alternatives

Statistics	CC	CM	SC	SS	SW	WC	WW
Mean	18.99	16.70	15.24	13.84	16.91	15.40	15.35
Median	18.98	16.59	15.23	13.86	16.94	15.36	15.10
Mode	---	---	---	---	---	---	---
Standard Deviation	1.89	2.67	2.12	1.52	1.97	1.40	2.32
Variance	3.57	7.15	4.49	2.30	3.87	1.97	5.37
Skewness	0.018	0.293	0.068	-0.099	-0.064	0.177	0.714
Kurtosis	2.46	3.14	2.78	2.76	2.89	2.78	3.95
Coeff. of Variability	0.099	0.160	0.139	0.109	0.116	0.091	0.151
Minimum	14.01	8.81	8.25	8.08	9.38	12.04	10.08
Maximum	23.93	27.76	22.82	17.96	23.75	21.93	30.59
5% Percentile	22.0	21.0	19.0	16.0	20.0	18.0	20.0
50% Percentile	19.0	17.0	15.0	14.0	17.0	16.0	15.0
70% Percentile	18.0	15.0	14.0	13.0	16.0	15.0	14.0
95% Percentile	16.0	13.0	12.0	11.0	14.0	13.0	12.0

Table 7.24 Statistics of the LEED scores obtained by sustainable alternatives

Statistics	GCC	GCM	GSC	GSS	GSW	GWC	GWW
Mean	35.50	34.35	38.28	38.07	45.74	39.03	41.55
Median	35.00	34.00	38.00	38.00	46.00	39.00	42.00
Mode	34.00	31.00	36.00	37.00	45.00	39.00	43.00
Standard Deviation	6.00	7.04	7.37	3.39	5.71	7.22	5.03
Variance	35.99	49.58	54.33	11.52	32.58	52.19	25.35
Skewness	0.1612	0.5569	0.5441	0.3438	0.0341	0.5497	0.0809
Kurtosis	3.08	3.40	3.44	2.82	2.95	3.59	2.97
Coeff. of Variability	0.1690	0.2050	0.1926	0.0891	0.1248	0.1851	0.1212
Minimum	15.00	17.00	18.00	29.00	26.00	19.00	24.00
Maximum	64.00	72.00	78.00	47.00	70.00	75.00	61.00
5% Percentile	46.0	47.0	52.0	44.0	55.0	52.0	50.0
50% Percentile	35.0	34.0	38.0	38.0	46.0	39.0	42.0
70% Percentile	32.0	30.0	34.0	36.0	43.0	35.0	39.0
95% Percentile	26.0	24.0	27.0	33.0	36.0	28.0	33.0

Figures 7.25 and 7.26 summarize the cumulative probability distributions of the sustainability criterion represented by the assessed LEED score for the conventional alternatives (figure 7.25) and by the LEED scores obtained by the sustainable alternatives (figure 7.26). The sustainability assessment model for conventional school buildings shows that the highest LEED scores can be obtained by applying the precast concrete alternative (CC), which achieved scores in the range of 16 - 19 at the three tested confidence levels. The second-highest possible scores could be obtained by steel buildings with wood façades (SW) with scores between 14 and 17, followed by the concrete with cavity walls alternative (CM). CM structures could obtain LEED scores of 13 to 17 at the 95% and 50% confidence levels, respectively. The model also indicates that the minimum sustainability score would be obtained by a pure steel alternative (SS), with a LEED score of between 11 and 14 at the 95% and 50% confidence levels.

The cumulative distributions of the sustainable alternatives in figure 7.26 indicate that the highest LEED score can be obtained by using a steel structure with wood facades (GSW). GSW attained LEED scores of 36 to 46 at the three confidence levels tested. The second-highest scores were achieved by the all-wood alternative (GWW), with LEED scores of 33 and 42 at the 95% and 50% confidence levels. The alternative that received the lowest sustainability score was concrete with cavity walls (GCM), with 24 and 34 LEED points at the 95% and the 50% confidence levels, respectively. Using steel structure with wood facades (GSW) instead of the low-scoring (GCM) increases the level of sustainability by 50% and 35% at the 95% and 50% percentile, respectively.

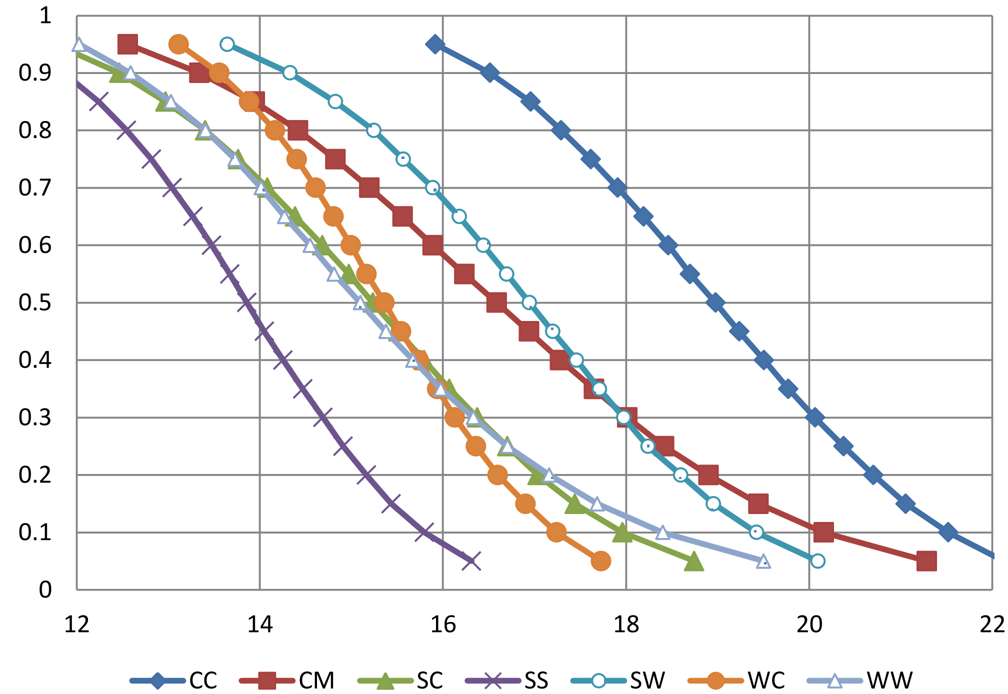


Figure 7.25 Cumulative probability distributions of the LEED scores estimated for the various conventional alternatives

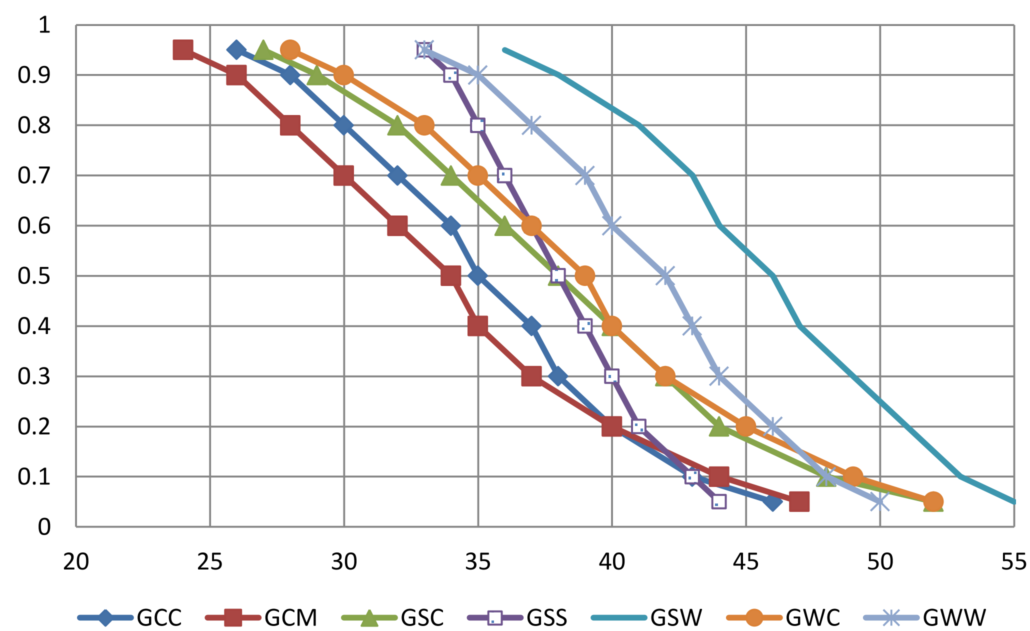


Figure 7.26 Cumulative probability distributions of the LEED scores obtained by the various sustainable alternatives

Table 7.25 presents the probable minimum utility scores achievable for sustainability criterion by each of the various alternatives over all three tested confidence levels. The result of the selection framework indicates that each structure and envelope type has a different influence on the sustainability performance for conventional and LEED certified school buildings. The sustainability criterion that ranks first is the sustainable steel alternative with wood facades, (GSW), with scores of 12.2, 14.6, and 15.6 out of 19 at the 95%, 70%, and 50% confidence levels, respectively. The second-highest scores are achieved by the sustainable all-wood alternative (GWW), while the conventional steel alternative (SS) received the lowest scores. The minimum utility scores most likely to be achieved by the different alternatives range between 3.84 – 12.24, 4.42 – 14.62, and 4.43 – 15.64 for the three confidence levels.

Table 7.25 Minimum obtained scores & the alternatives' ranking of sustainability criteria for the three confidence levels

Alternatives	95% percentile		70% percentile		50% percentile (Median)	
	Minimum score	Ranking	Minimum score	Ranking	Minimum score	Ranking
CC	5.41	8	6.09	8	6.46	8
CM	4.29	11	5.17	10	5.65	10
SC	4.01	13	4.80	11	5.17	12
SS	3.84	14	4.42	14	4.73	14
SW	4.63	9	5.41	9	5.75	9
WC	4.46	10	4.97	10	5.24	11
WW	4.08	12	4.76	12	5.14	13
GCC	8.84	6	10.88	6	11.90	6
GCM	8.16	7	10.20	7	11.56	7
GSC	9.18	5	11.56	5	12.92	5
GSS	11.22	3	12.24	3	12.92	4
GSW	12.24	1	14.62	1	15.64	1
GWC	9.52	4	11.90	4	13.26	3
GWW	11.22	2	13.26	2	14.28	2

7.5.6 Selection of Favorable Alternatives based on the Stochastic Approach

Probabilistic simulation results allow alternatives to be compared at different levels of risk, enabling school boards to make better-informed decisions. The results of the developed selection framework are presented at three different levels of confidence, or alternatively, against various levels of risk. The first result is presented at a 95% confidence level with an associated 5% level of risk. The second result is computed at a 70% confidence level where there is a 30% level of risk. The last result is for a 50% confidence level, or at the median, where a risk has a strong probability at 50%. The selection framework enables decision makers at school boards to select their favorable structure and envelope types for their new school building according to their own acceptable level of risk. Higher utility scores indicate lower LCC and a higher level of sustainability. Table 7.26 presents the overall minimum utility scores achievable by the various alternatives, for all the selection criteria. A minimum achievable utility score indicates that a school structure can achieve a utilities score value that is equal to or more than the computed value in the table. Decision makers are asked to define the acceptable risk level so they can make their own well-informed decision accordingly. The output of the three tested levels of confidence can be demonstrated in the following result summary:

7.5.6.1 Selection at the 95% Confidence Level

In this case, the total probable achieved scores are somewhat low due to the low risk level, which will probably cause higher LCCs and lower sustainability levels compared to the other confidence levels. The minimum utility scores likely to be achieved by the different alternatives range from 24.26 to 36.34 at this risk level. The most favorable structure and exposure type at the 95% confidence level with a 5% risk level is the green precast concrete alternative (GCC). There is a 5% chance that the total score of the selected alternative will be less than 36.34 out of 100, or alternatively, there is a 95% chance that the total score will be greater than or equal to 36.34. The second most-favorable alternative is the green concrete structure with cavity walls (GCM), which can achieve a minimum score of 31.16, and the third most-favorable one is the green steel with wood facades (GSW), which can achieve a minimum score of 31.13. The least-preferred alternative is the conventional precast concrete facades (CC), which can only achieve a minimum score of 24.26, as shown in table 7.26. Applying a favorable alternative like the green precast concrete (GCC) can achieve scores that are 50% higher than those of the least-preferred option, CC.

7.5.6.2 Selection at the 70% Confidence Level

This level has total probable achieved scores that are higher than those in the 95% confidence situation since there is now a higher risk level, which will probably cause lower LCCs and higher sustainability levels. The minimum probable utility scores achieved by the different alternatives range from 39.46 to 56.59 at this confidence level. The highest minimum score achieved in this confidence level exceeds the highest minimum obtained score of the previous level by about 55%, while the lowest minimum obtained score is higher than the highest minimum value at the 95% confidence level.

The most-favorable structure and exposure type at the 70% confidence level with a 30% level of risk is the green concrete alternative with masonry walls (GCM). There is a 30% chance that the total obtained score of the selected alternative will be less than 56.59 out of 100, or alternatively, there is a 70% chance that the total score will be equal to or greater than 56.59. The second-favorable alternative is green precast concrete (GCC), which can achieve a minimum score of 54.67, and the third most-favorable one is the conventional precast concrete (CC), which can achieve a minimum score of 49.71. The least-preferred alternative is the conventional steel structure with steel facades (SS), which can only achieve a minimum score of 39.46, as shown in Table 7.26. Applying the most-favorable alternative, GCM, can achieve scores that are 44% higher than those of the least-preferred one, GWC.

7.5.6.3 Selection at the 50% Percentile Confidence Level

In this case, the total probable achieved scores are much higher than in the previous case, as the increased risk level will minimize the LCCs and maximize the sustainability level compared to the 70% confidence level. The minimum utility scores likely to be achieved by the different alternatives range from 47.90 to 69.02 at this confidence level. The highest minimum score achieved in this confidence level exceeds the highest minimum score obtained in the prior confidence level (70%) by about 23%, while the lowest minimum score is higher than the previous level’s lowest minimum by about 20%.

The most-favorable structure and exposure type at the 50% confidence /50% risk level is the green concrete alternative with masonry walls (GCM). There is a 50% chance that the GCM's total obtained score will be less than 69.02 out of 100, or alternatively, there is a 50% chance that the total score will be equal to or greater than 69.02. The second most-favorable alternative is the green precast concrete alternative (GCC), which can achieve a minimum score of 66.37, and the third most-favorable one is the green steel structure with concrete brick facades (GSC), which could achieve a minimum score of 61.45. The least-preferred alternative is the conventional pure steel (SS), which could only achieve a minimum score of 47.90, as demonstrated in Table 7.26. Applying the most-favorable alternative, (GCM), can achieve scores that are 47% higher than those of the least-preferred one option, (SS).

Table 7.26 Total minimum obtained scores & ranking of alternatives over all the selection criteria for the various confidence levels -- deterministic approach

Alternatives	95% percentile		70% percentile		50% percentile (Median)		Deterministic Approach	
	Minimum score	Ranking	Minimum score	Ranking	Minimum score	Ranking	Utilities score	Ranking
CC	24.26	14	49.71	3	58.71	4	57.89	5
CM	25.60	13	48.16	4	57.28	5	56.04	7
SC	26.55	12	41.30	12	50.84	9	50.34	9
SS	27.78	8	39.46	14	47.90	14	49.38	10
SW	28.21	7	41.51	11	49.89	11	51.51	8
WC	28.64	6	43.01	9	51.50	8	48.66	11
WW	29.08	5	42.38	10	50.50	10	47.44	12
GCC	36.34	1	54.67	2	66.37	2	65.17	1
GCM	31.16	2	56.59	1	69.02	1	64.70	2
GSC	27.19	9	47.40	6	61.45	3	56.06	6
GSS	27.05	10	47.98	5	56.61	6	58.19	4
GSW	31.13	3	46.89	7	53.82	7	60.51	3
GWC	26.55	11	40.60	13	48.40	13	45.34	14
GWW	30.90	4	43.22	8	49.64	12	46.20	13

7.5.7 Risk Assessment

The risk assessment or analysis is performed using Efficient Frontier analysis to enhance the analysis of the framework's output. Efficient Frontier analysis calculates the curve that plots the means of the various alternatives against changes to the probabilistic standard deviation of the same alternatives. This analysis allows comparisons of the project mean costs against different levels of risk to enable decision makers at school boards to make well-informed decisions. In this study, the risk assessment using the Efficient Frontier is performed on the best seven among the fourteen alternatives in order to enhance the resulting selection framework. The best alternatives include conventional and sustainable precast concrete alternatives (GCC, CC), conventional and sustainable concrete with cavity walls (CM, GCM), and sustainable steel structures with the various exposure types, (GSS, GSW, and GSC).

Risk assessment is applied on the net present values of the whole life cycle costs. The NPV of the seven alternatives are computed using Monte Carlo simulation to address the associated uncertainties with LCC parameters. Figure 7.27 presents the probability distribution of the NPV for four conventional and sustainable alternatives. The statistics NPV statistics of the whole LCC for the best seven alternatives are summarized in table 7.26

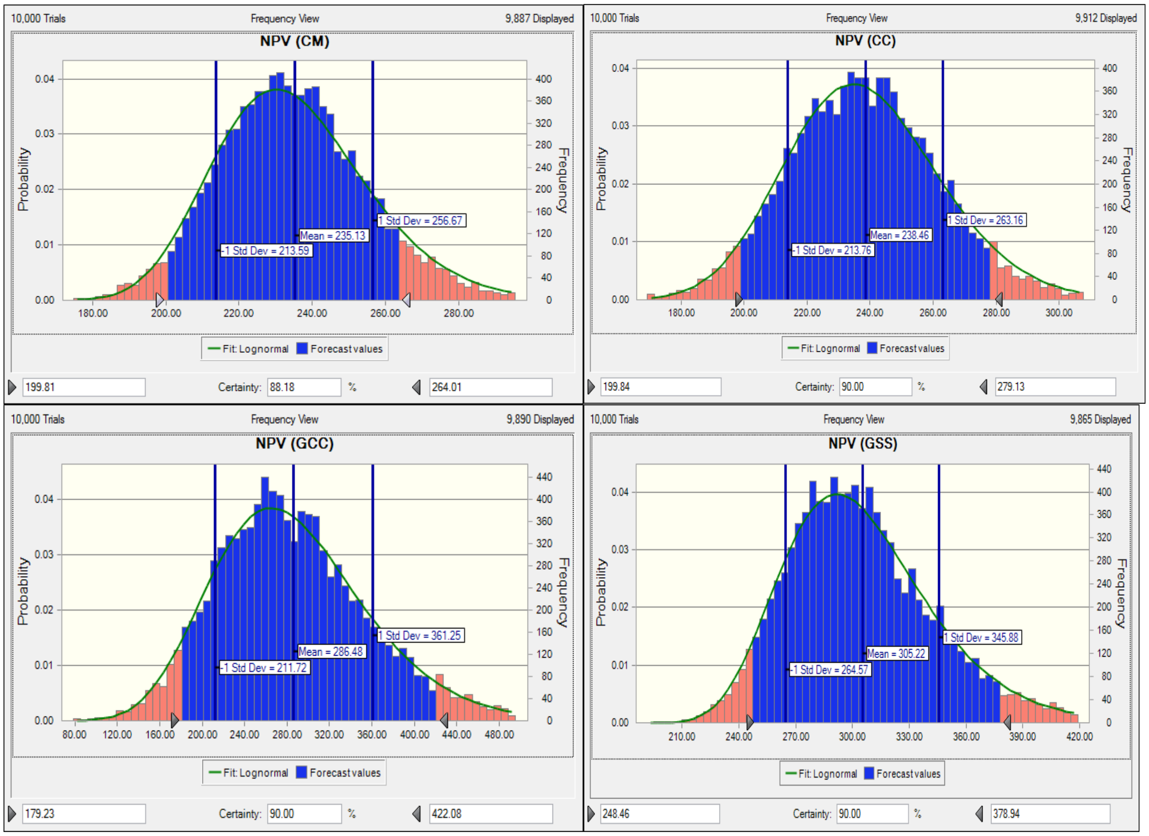


Figure 7.27 Probability distribution of the NPV for four conventional and sustainable alternatives

Table 7.27 Statistical details of the overall NPV in \$/ft² for the seven best alternatives

Statistics	CC	CM	GCC	GCM	GSC	GSS	GSW
Mean	238.92	234.77	285.72	275.84	426.00	305.09	345.44
Median	238.25	233.74	277.76	244.24	379.53	299.79	371.40
Mode	---	---	---	---	---	---	---
Standard Deviation	25.21	21.45	75.77	132.89	168.46	40.95	81.25
Variance	635	460	5,741	17,658	28,380	1,677	6,600
Skewness	0.5957	0.6588	0.6692	8.02	6.33	0.8908	-0.4811
Kurtosis	5.72	5.09	3.92	159.43	85.46	4.59	1.85
Coeff. of Variability	0.1055	0.0914	0.2652	0.4817	0.3955	0.1342	0.2352
Minimum	152.16	164.91	28.24	-295.68	271.19	205.66	153.94
Maximum	484	417	756	4,555	4,215	568	484
5% Percentile	200	202	177	180	307	249	206
50% Percentile	238	234	278	244	380	300	371
70% Percentile	251	244	317.86	281	433	321	410
95% Percentile	280	271	420	468	686	380	443

Figure 7.28 displays a plot of the objective value (mean of the NPV of the LCC) for the different alternatives against their standard deviation. The mean values range from \$234 to \$426/ft^2, while the standard deviation values lie between \$21.4 and \$168/ft^2.

It is somewhat difficult to obtain smaller means of the NPV without generating higher standard deviations, or to lower standard deviations without generating higher NPV means. This method uses the mean and standard deviation of the project cost as the criteria for balancing risk and reward with regard to sustainability criteria. Thus, the decision makers must face the trade-off between smaller NPVs with higher risk, and higher NPVs with lower risk, when taking into account the sustainability principles.

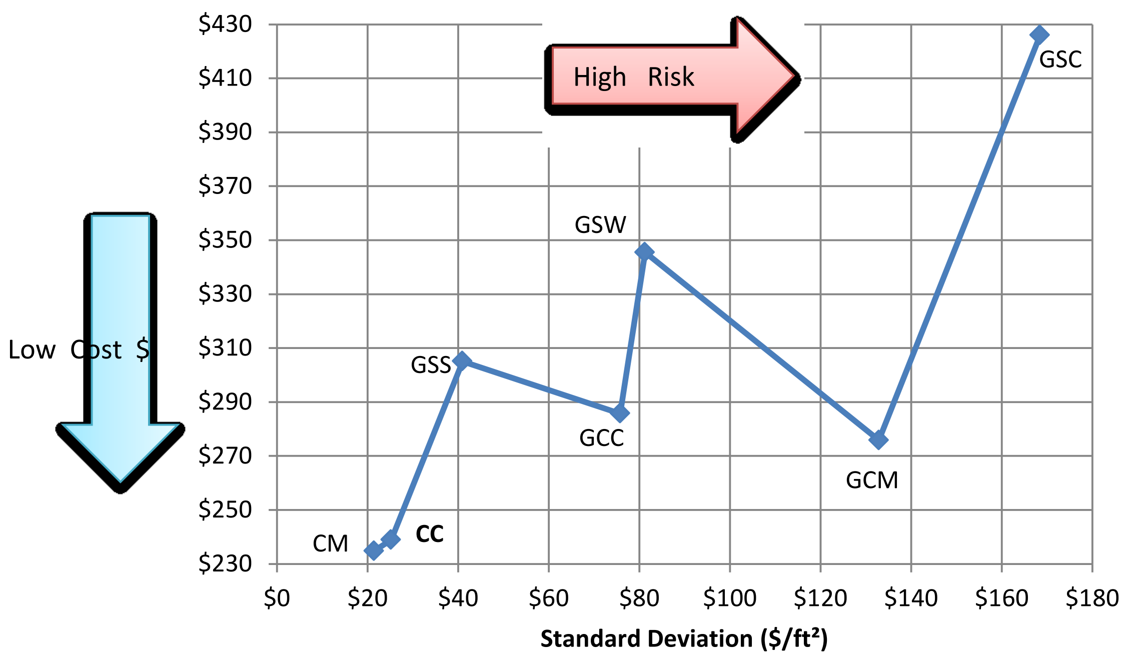


Figure 7.28 Risk assessment using Efficient Frontier Analysis of the overall net present value for the best seven alternatives

In this assessment, the conventional concrete alternative with cavity walls (CM) has the lowest mean value, $234.7/ft^2, and the lowest risk value, $21.4/ft^2. The second-lowest mean value is recorded for conventional precast concrete (CC), with its mean value at$238.9/ft^2 and its low risk value of $25.2/ft^2. Although these alternatives are not risky and have low means values, they will not be selected because they do not meet the sustainability requirements.

The highest mean value with the highest risk is recorded for sustainable steel structures with concrete brick (GSC). The mean NPV for this alternative is $426.0/ft^2 and the standard deviation value is $168.4/ft^2. This alternative is eliminated from selection because of its high mean value and its high associated risk. The second-highest mean value is recorded at $345.4/ft^2 with an associated standard deviation of $81.2/ft^2 for sustainable steel with wood facades (GSW). Even though this alternative reduces risk by about 52% compared to the highest risk value, the mean value is still high compared to the other alternatives. Hence, this alternative would not be very attractive to decision makers.

The selection becomes focused on three alternatives, as displayed in Figure 7.28. The lowest risk among these alternatives generates the highest mean value for sustainable steel structure with steel siding facades,(GSS). The standard deviation of this alternative is recorded at $40.95/ft^2 and the mean value is $305 /ft^2. In contrast, the alternative with the lowest mean value generates high risk -- sustainable concrete structure with masonry walls (GCM). The mean value for this alternative is recorded at $275.8/ft^2 and the associated standard deviation is $132.8/ft^2.

These two alternatives might not be very attractive for decision makers because the steel alternative has a high mean value while the concrete alternative has a high risk.

The last alternative is the sustainable precast concrete (GCC) structure. This alternative has values that fall in-between the highest and lowest mean and risk values of the two previous alternatives. Its mean value is 285.7/ft^2, while the risk value is about $75.7/ft^2. Applying this alternative will reduce the mean value by 7%, while the risk will be reduced by 44% compared to the other alternatives.

The risk assessment result indicates that the sustainable precast concrete alternative (GCC) is the most attractive alternative for decision makers in school boards due to its moderate mean and risk value in relation to sustainability principles. Although the risk assessment of NPV resulted in the selection of this sustainable precast concrete alternative (GCC) as the most attractive option, it may be even more advantageous for decision makers to choose a sustainable steel alternative (GSS) to minimize the risk, or to select the concrete alternative with cavity walls to minimize the mean value.

The risk assessment process also can be performed on the significant criteria. Since the running costs were deemed as having the highest relative weight

(33%) by the experts, risk assessment is performed on them to select the most attractive alternative. Figure 7.28 displays a plot of the objective mean value of running costs for the seven alternatives against their standard deviation.

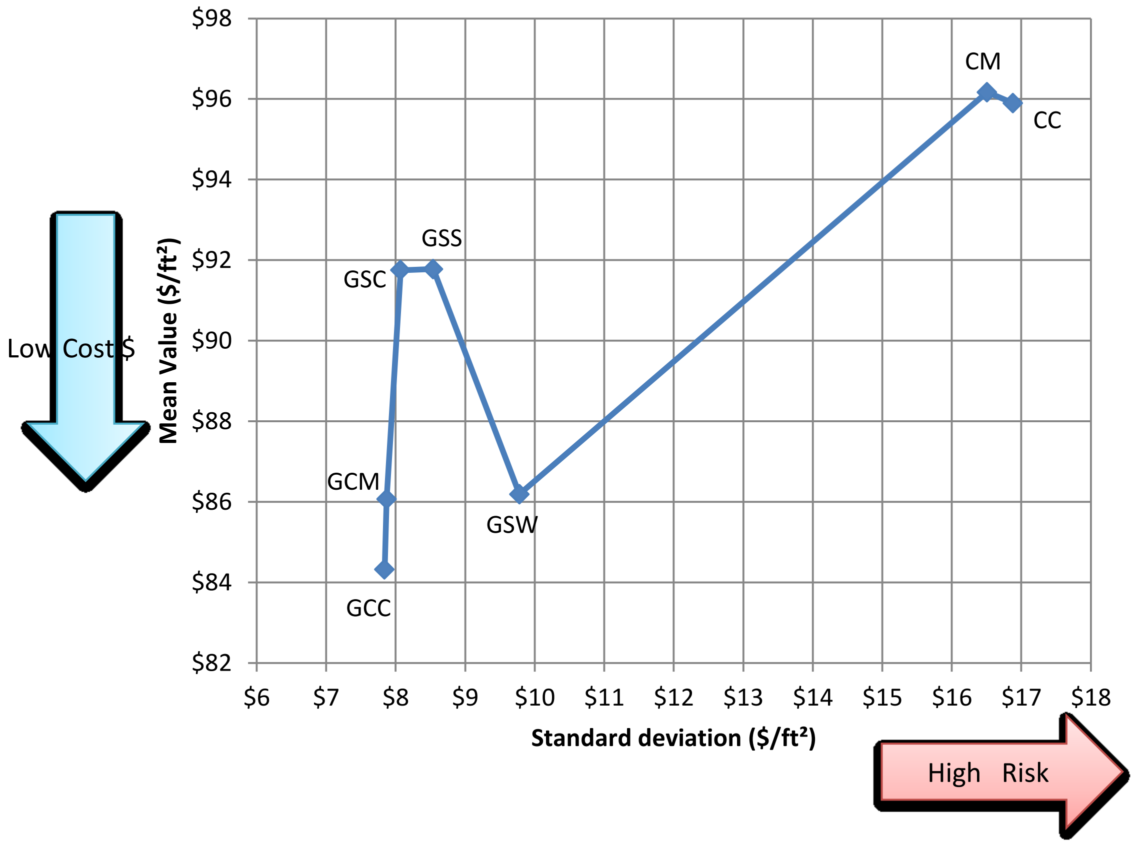


Figure 7.29 Risk assessment using Efficient Frontier Analysis of the PV of the running costs criterion for the best seven alternatives

Risk assessment is performed on the running costs criterion using the Efficient Frontier method. The result shows that it is very likely to obtain smaller mean values of running costs with smaller standard deviations, and to obtain higher mean values with higher standard deviations, as shown in Figure 7.29.

The conventional concrete alternatives, (CM) and (CC), have the highest mean values of($95.9/ft^2 and $96.2/ft^2, while their standard deviations are between $16.5/ft^2 and $16.9/ft^2.

The sustainable precast concrete alternative (GCC) proves to have the smallest mean running cost value $84.3/ft^2 with the lowest obtained risk at $7.84/ft^2. This option is followed by the sustainable concrete alternative with cavity walls, or GCM. Thus, the risk assessment of the running costs criterion proves that the GCC alternative is the option most attractive to decision makers.

In conclusion, risk assessments are performed on both the NPV and running cost criteria using the Efficient Frontier method, which depends mainly on the mean values of the alternatives and their associated standard deviations. Both risk assessments indicate that the sustainable precast concrete alternative (GCC) is the most attractive option for decision makers in school boards.

The risk assessment process using Efficient Frontier Analysis can be also applied to other selection criteria or to evaluate criteria that are of concern to the decision makers.

7.6 Validation of Developed Models and Framework

Previous parts of this thesis describe the development of the LCC and sustainability assessment models in detail, as well as the selection framework. To further enhance these tools and to assure their viability, evaluation and validation procedures were applied on them. The validations were performed to confirm the results and to verify the data used. The evaluation procedures were divided into several parts as listed below;

- Validation of initial costs
- Validation of energy costs
- Validation of operating and maintenance costs
- Validation of major repairs costs
- Validation of environmental impact costs and market price of CO_2e.
- Validation of salvage values.

7.6.1 Validation of initial costs

Since the initial costs for the conventional alternatives were computed using real market prices obtained from RS Means 2011, no further validation was required; nonetheless, a validation was performed to double check this data. Information was gathered from the "The 2011 School Construction Report" (16th Annual Report of the school planning and managements in US). Table 7.28 displays the profile of new schools currently underway in the USA. The study investigates close to 360 new school buildings throughout the U.S.; 201 elementary schools;

68 middle schools; 91 high schools. The national median cost per square foot for construction of an elementary school in 2011 was $190.48. One quarter of all school districts (the lower 25 percent) are spending $156.72 per square foot or less for its elementary school construction while one quarter of all districts are spending $268.24 per square feet or more. One in 10 school districts' estimated cost for a new elementary school comes to almost $548.5 per square foot, as shown in table 7.28.

Table 7.28 Profiles of new schools currently underway in USA (Abramson 2011)

National Medians	$/Sq. Ft.	$/Per Student	Sq. Ft./ Per Student	No. of Students	Building Size (Sq. Ft.)	Building Cost ($000's)
Elementary Schools	$190.48	$25,500	125.0	600	75,000	$14,800
Middle School	$215.14	$29,959	149.0	936	140,000	$30,000
High Schools	$188.68	$30,833	156.3	1,600	260,000	$54,900
Low Quartile	**$/Sq. Ft.**	**$/Per Student**	**Sq. Ft./ Per Student**	**No. of Students**	**Building Size (Sq. Ft.)**	**Building Cost ($000's)**
Elementary Schools	$156.72	$18,962	106.7	500	64,000	$11,600
Middle School	$172.41	$23,774	124.0	750	101,000	$21,000
High Schools	$164.46	$25,769	125.0	1,200	150,000	$32,000
High Quartile	**$/Sq. Ft.**	**$/Per Student**	**Sq. Ft./ Per Student**	**No. of Students**	**Building Size (Sq. Ft.)**	**Building Cost ($000's)**
Elementary Schools	$268.24	$36,667	140.0	800	95,000	$22,755
Middle School	$248.65	$36,667	162.2	1,200	170,000	$41,000
High Schools	$252.50	$42,037	187.5	2,064	342,000	$75,534
Top 10 Percent	**$/Sq. Ft.**	**$/Per Student**	**Sq. Ft./ Per Student**	**No. of Students**	**Building Size (Sq. Ft.)**	**Building Cost ($000's)**
Elementary Schools	$548.51	$49,000	166.7	1,000	120,000	$34,511
Middle School	$294.12	$50,000	176.3	1,300	190,000	$47,000
High Schools	$500.57	$56,442	225.0	2,400	400,000	$113,356

7.6.1.1 Conventional Schools

The regression models developed in this study indicate that the means of the initial costs for conventional elementary school buildings in Montreal are $137.2 to $185.0, for wood structures (WW) and precast concrete alternatives (CC), respectively. At the 95% confidence level, these same options range from $146.2 to $209.5. These values are assumed to be valid since they fall between $156.72 and $190.48 for the lowest quartile and the national median cost, respectively. Table 7.29 display the square footage initial costs for conventional and sustainable alternatives.

Table 7.29 Computed mean and 95% confidence level values of IC (in $/ft2) for all 14 alternatives

Conventional Alt.	**CC**	**CM**	**SC**	**SS**	**SW**	**WC**	**WW**
Mean	$184.96	$174.96	$161.76	$154.71	$156.29	$142.78	$137.15
95% percentile	$209.48	$191.89	$176.45	$163.32	$165.70	$156.18	$146.16
Sustainable Alt.	**GCC**	**GCM**	**GSC**	**GSS**	**GSW**	**GWC**	**GWW**
Mean	$262.26	$240.96	$287.75	$244.01	$297.35	$312.44	$386.22
95% Percentile	$391.64	$428.10	$547.35	$315.46	$378.42	$534.18	$681.98

7.6.1.2 Sustainable Schools

Initial costs data for LEED certified schools was gathered mainly from the US Green Buildings Council website and other websites. Most of the data was gathered from three different sources for each school building, which helps to prove the validity of the data.

Since green school buildings comprise a considerable percentage of new schools and since they have high initial costs, the top 10% of these costs are assumed to have been computed for these schools. The means of initial costs for sustainable elementary school buildings in Montreal are found to be between $240.9 and $386.2, for green concrete alternatives (GCM) and green wood alternatives (GWW), respectively. These same options' initial costs' means are from \$315.5 to\$681.9 at the 95% confidence level. These values are assumed to be valid since that they fall between \$268.2 and \$548.48 for the highest quartile and the top 10%, as displayed in tables 7.28 & 7.29.

7.6.2 Validation of Energy costs (EC)

Energy consumption was measured in this study using the energy simulation software eQUEST. The energy simulations were performed based on application of the advanced energy design guide for K-12 school buildings. This guide is derived from the ASHRAE 90.1 standard, and it is similarly aimed at achieving 30% in energy savings. Table 7.30 displays the annual energy consumption reduction for the different alternatives. The resulting average energy savings is 32.4%, very close to that achieved by applying the K-12 AEDG to reduce consumption by 30%. The energy consumption reduction is therefore assumed to be valid.

Table 7.30 Annual energy consumption reduction achieved by applying theK-12 AEDG requirements

Structure & Envelope Type	SS	WW	CC	CM	SC	WC	SW
Energy Consumption (KWh/ft^2)	17.41	17.39	17.43	17.47	17.42	17.41	17.39
Energy Reduction (Percentage %)	32.48%	32.54%	32.40%	32.25%	32.46%	32.48%	32.54%

The utilities rates that were used are valid since they were gathered from the English Montreal school board, (EMSB), based on real data. In addition, energy cost data for 18 conventional school buildings in Montreal was gathered from the EMSB as can be seen in table 7.31. This data indicates that the square footage energy costs vary between \$1.40 and \$2.31/ft^2, with an average value of \$1.90/ft^2. The measured and computed energy costs for the different conventional alternatives vary between \$1.87 and\$2.01/ft^2. Hence, the energy costs are found to be valid.

The energy costs for sustainable school buildings are assumed to be valid since they were computed based on the energy reductions gathered from the green buildings council in US USGBC. The reductions were estimated based on the ASHRAE 90.1 baseline and the costs computed accordingly.

Table 7.31 Square footage energy costs for 18 schools in Montreal (EMSB 2011)

School No.	School 1	School 2	School 3	School 4	School 5	School 6	School 7	School 8	School 9
Energy cost	\$1.88	\$2.31	\$1.63	\$1.75	\$1.86	\$1.93	\$1.40	\$1.59	\$2.05
School No.	school 10	school 11	school 12	school 13	school 14	school 15	school 16	school 17	school 18
Energy cost	\$1.67	\$1.80	\$1.87	\$2.30	\$2.15	\$1.54	\$1.75	\$2.41	\$2.27

7.6.3 Validation of Operating and Maintenance costs (O&M)

Operating and maintenance cost data was gathered from the Lester B. Pearson School Board in Montreal. It is representative of the national average costs for the province of Quebec, which confirms the validity of the data. A second validation was realized from the 37th Annual Maintenance & Operations Cost Study on school buildings in the USA. Table 7.32 displays the detailed O&M costs, which shows an average of \$3.31/ft^2 excluding energy costs. The O&M costs that were applied range between \$3.43 and \$2.82/ft^2 for elementary and high schools, respectivly. The O&M costs utilized in this study can therefore be assumed to be valid.

Table 7.32 O&M costs for school buildings in the USA (Agron 2008)

Total Payroll	**$2.05**
Custodial**	$1.61
Maintenance**	$0.53
Grounds**	$0.22
Outside Contract Labor	**$0.21**
Total Energy/Utilities	**$1.52**
Energy (gas, electricity, other fuels)**	$1.25
Utilities**	$0.22
Trash Collection/Disposal**	$0.05
Total Equipment & Supplies	**$0.38**
Custodial/Maint. Equip. & Supplies**	$0.27
Grounds Equip. & Supplies**	$0.06
Other	**$0.40**
Total M&O Budget*	**$4.56**
Total District Expenditures (TDE)	**$58.69**

7.6.4 Validation of Major Repairs Costs (MRC)

Major repairs costs data was gathered from various school boards in North America. This gathered data consists of information from approximately 400 conventional elementary and high schools. Since this information was gathered from school boards for real, existing projects, it is considered to be valid. The collected MR data showed significant fluctuation among buildings that have the same structure and envelope type. This fluctuation indicates that the uniqueness of each building, as it passes through different circumstances such as quality of construction, building usage, weather effects, age and so on. This fluctuation could also indicate that some of this information was incomplete, in which case more investigation and validation would be required. Table 7.33 presents the statistical detail of the collected major repair cost data for various alternatives. The data analysis showed that the minimum computed annual MR cost was close to $0.32-$0.80/ft^2 at 5% percentile, while the maximum varied between $2.97- $3.24/ft^2, at 95% percentile based on structure type. At 70% percentile, the costs are varied $1.39- $2.18/ft^2 as displayed in table 7.33.

Table 7.33 Statistical results for major repair costs for various structure types

Alternative	5% percentile	95% percentile	70% percentile	Mean
Steel	$0.62	$3.24	$1.99	$1.70
Wood	$0.80	$2.94	$2.18	$1.90
Concrete	$0.32	$2.97	$1.39	$1.25

The data gathered from the Lester B. Pearson School Board in Montreal indicates that the average annual MR cost is about $2.0/ft^2 (LBPSB 2011). The mean values of MR costs are $1.25, $1.70, and $1.90/ft^2 for concrete , steel, and wood alternatives, respectively. Since most schools in Montreal were built as steel and wood structures, the statistical results confirm the validtiy of this information.

7.6.5 Validation of Environmental Impact Costs (EIC)

7.6.5.1 Validation of CO_2e Quantification

The CO_2e quantification (in tonnes) is assessed using ATHENA Impact Estimator for Buildings. It is the only software tool in North America that evaluates whole buildings and assemblies based on LCA methodology. Since this software is designed in Canada, the results of this assessment are expected to be valid for this study.

For additional validation, a green building that achieved silver LEED certification, the Thomas L. Wells Public elementary school in Toronto, was evaluated. . This school was designed to provide 35% energy savings over the baseline, where the estimated annual carbon footprint is 9 lbs. CO_2/ft^2 (46 kg CO_2/m^2) (Malin 2012). Since the case study is treated as being in Montreal, and since Montreal and Toronto are located in exactly the same climate zone (6A) and both are urban settings, no energy adjustment was required. The comparison between the actual and the estimated can be evaluated as follows:

- The CO_2 index factor for Montreal is 80.1, while it is 81.6 for Toronto according to the US and Canada Green City Index (Siemens 2011). The adjustment is therefore (81.6/80.1) = 1.019 X 9.0 = 9.17 lbs. CO_2/ft^2
- The assumed adjustment factor to convert a green school to a conventional one, or (X percentage of energy reduction %) = 1.35 x 9.17 = 12.37 lbs. CO_2/ft^2
- The environmental impact calculated using ATHENA® is 89.12 (Kg CO_2e/ft^2)/ 20 = 10.15 lbs. CO_2/ft^2.

  Validation = estimated/actual = 10.15/12.37= 82.0%; therefore the calculated quantity of CO_2 e is valid.

7.6.5.2 Validation of CO_2e Market Price

The applied CO_2e prices were provided from the current stock market trading listing (www.pointcarbon.com). In this market, countries and companies exchange their trading allowances on a formatted basis originally derived from the Kyoto Protocol. This market is monitored by the European commission, which affirm the validity of CO_2 market prices.

7.6.6 Validation of Salvage Values (SV)

Salvage value is computed in this study using the assumptions of the straight line depreciation method, which is commonly used in the depreciation of commercial buildings. This method depends essentially on the expected functional (useful) life of a school building. In this study, the functional or useful lives of various structure and envelope types are extracted from the Means Facilities Maintenance Standards. Therefore, the salvage values are considered to be valid.

7.6.7 Validation of Sustainability assessment (SUS)

The sustainability assessment results for conventional alternatives were validated as follows:

- Energy consumptions resulted from energy simulations were validated;
- LCA using ATHENA was found to be valid; and
- Material and resources were assumed to be valid since they were gathered from real data.

The sustainability assessments for sustainable school buildings are considered to be valid since they were gathered from real data (for LEED certified buildings) from the US Green Building Council.

CHAPTER 8: CONCLUSIONS, CONTRIBUTIONS, LIMITATIONS, RECOMMENDATIONS, AND FUTURE WORK

8.1 Conclusions

This research developed a Selection Framework, LCC Forecasting Models, and a Sustainability Assessment model to assist decision makers on school boards to select the best structure and exposure types of new school buildings based on LCC and sustainability criteria. Fourteen different conventional and sustainable alternatives were investigated using deterministic, stochastic, and risk assessment approaches to enhance the selection of the most attractive alternative.

The selection framework was developed using the AHP and the MAUT, based on experts' and decision makers' opinions that were gathered using a web-based questionnaire. The selection is performed based on the alternatives' performance in significant criteria, such as initial costs, running costs, environmental impact costs, salvage values, and sustainability principles (the LEED rating system).

A sustainability assessment model was developed to measure the LEED scores that could be achievable by the various conventional alternatives, based on energy consumption, reuse and recyclability, and life cycle assessment. The present values of life cycle components' costs were computed for the different alternatives for a period of 20 years of building operation in the City of Montreal at year 2011. Deterministic and stochastic LCC forecasting models were developed using the regression models of initial costs and the computed average values for the other cost components. A stochastic LCC model was adopted, which resulted in the selection of alternatives at three different confidence levels, 95%, 70%, and 50%. Risk assessment was applied on the net present value and running costs criteria using the Efficient Frontier method to enhance the selection process. The following conclusions can be stated, based on the research reported here:

- Incorporating life cycle assessment into LEED scoring in the sustainability assessment model is a significant means to measure the comprehensive sustainability performance of various structure and exposure types.
- Application of the recommendations of the AEDG for K-12 schools results in a valuable energy savings, and leads to equal energy performances for the various exposure systems.
- Performing an energy simulation for the various alternatives is a key part of any life cycle assessment, and is thus necessary to compute the associated environmental impact costs.
- Selecting an alternative based only on its performance in one life cycle stage typically leads to a wrong decision for the long term. All the life cycle stages should be considered in the selection process.
- Concrete and masonry school buildings proved to have high energy consumption rates and contribute more to global warming during their manufacturing, construction, and demolition stages. However, they proved to have lower annual energy consumption and less environmental impact

during their operating stage as well as throughout their overall life cycle span compared to other alternatives.

- The highest greenhouse gas (GHG) emissions are generated during the operating stage (90% of the overall effects) following by the manufacturing stage, while demolishing a building is found to contribute twice as much GHG emissions as the construction process.
- The most-favourable sustainable alternative is precast concrete (CC), which our model indicated could achieve the highest LEED scores, 15, 19, and 20, in three different scenarios, while the lowest sustainability level would be obtained by applying the pure steel alternative (SS), which only could obtain LEED scores of 7, 14, and 16.
- The averages of the LEED scores achieved in the material and resources category did not exceed 6 points out of 13 for any of the alternatives, which indicates the level of obstacles and gaps that still exist in the construction industry in terms of applying recyclability and the reuse of building materials.
- The regression models indicate that there is a positive correlation between the number of floors variable and the response variable (initial costs). At the same time, a negative correlation is identified between initial costs and school area as well as school level.
- Energy simulation results indicate that the square footage electricity consumption is higher in high schools than elementary schools, while annual gas consumption is lower in high schools.

- The minimum total gas consumption is recorded as 11.5 million kBtu for a precast concrete envelope,(CC), while the maximum consumption is recorded at 12.8 million kBtu for the standard steel alternative (SS), which indicates an annual savings of 1.3 million kBtu when a concrete system is applied.
- The expected annual energy cost saving when a precast concrete envelope is applied is close to \$10,000 for a 75,000ft^2 elementary school building, and about \$20,000 for a 250,000ft^2 high school building.
- In Montreal, natural gas production and consumption have a higher environmental impact than the production and consumption of electricity because hydropower is used to generate electricity.
- The averages of the relative weights of criteria are computed based on experts' opinions as 25% for initial costs, 33% for running costs, 13% for environmental impact costs, 10% for salvage value, and 19% for sustainability principles.
- The initial costs represent about 56% and 79% of the total NPV for conventional wood schools (WW) and precast concrete buildings (CC), respectively while these costs represent approximately 80% and 92% of the total NPV for sustainable wood schools (GWW) and sustainable precast concrete schools (GCC), respectively.
- The minimum initial cost is recorded as \$136/ft^2 for wood schools (WW) and the maximum initial cost is \$384/ft^2 for green wood schools (GWW), a difference of close to 180%.

- The minimum running cost value is recorded at $83.7/ft^2 for green precast concrete schools (GCC) and the maximum as $106.9/ft^2 for conventional wood schools (WW).
- The minimum EIC value is recorded at $0.5/ft^2 for the green steel alternative with wood facades (GSW), while the maximum EIC is $1.02/ft^2 for conventional steel schools (SS).
- The maximum salvage value is recorded at $59.1/ft^2 for a sustainable precast concrete school (GCC), and the minimum salvage value is as low as $0.0/ft^2 for conventional and sustainable wood schools (WWs) and (GWWs).
- The LEED scores range from 46 for sustainable steel with exterior wood walls (GSW) to 35 for the green concrete with masonry walls (GCM) option.
- The selection framework indicates that its ranking of alternatives is completely different than that of the NPV method. The NPV method concludes that the conventional alternatives are more cost effective compared to the sustainable alternatives, which would lead to in inappropriate selections and higher associated costs.
- The selection of the most-favourable alternative is complicated and is affected by the approach utilized: deterministic, stochastic at 95%, 70%, and 50% confidence levels, and risk assessment using the Efficient Frontier method.

- The selections based on the deterministic approach are almost equivalent to the selections at the 50% percentile confidence level, which indicates a high risk level.
- Exceeding the acceptable risk level resulted in achieving high total scores, which indicates higher associated sustainability levels and lower life cycle costs.
- Conventional concrete alternatives proved to have the highest initial costs, but they also have the lowest overall LCC (lowest NPV), while wood alternatives have the lowest initial costs and the highest NPV.
- The first two ranks are occupied alternately by sustainable precast concrete alternatives, (GCC) and sustainable concrete with cavity walls (GCM).
- No significant correlations were detected between school parameters such as area and number of floors and some life cycle components such as operating and maintenance costs, major repairs' costs, and initial costs of a sustainable school building.
- There are also no significant correlations between the LEED scores obtained and the initial costs, since some LEED scores were easily obtained with no or low cost premiums, while others required high costs, which helps to interpret the high fluctuations and standard deviations in the initial costs.
- The risk assessment technique using the Efficient Frontier method is a powerful tool that enhances the selection of the most attractive alternative.

- LEED certified buildings prove to have higher initial costs with higher standard deviations based on their structure and exposure systems; however they also prove to have lower running costs with lower standards deviation than conventional buildings.
- Structure and exposure types prove to have a very significant influence on LCC and sustainability, which reinforces importance of this research. Therefore, new school construction decisions should be made based on structure and envelope types.
- The sustainable precast concrete alternative (GCC) was selected as the most attractive or favorable alternative based on the deterministic approach, a stochastic approach at a 95% percentile confidence level, and according to a risk assessment of the NPV and running costs.
- This research provides a realistic framework to assist governments in minimizing their expenditures and to assist them to overcome their economic crises. It also aims to reduce greenhouse gas emissions and minimize the environmental impact of new buildings, which will contribute to the reduction of global warming and the depletion of resources.

8.2 Contributions

This research project achieved the following:

- Development of a selection framework for structure and envelope types for new school buildings based on life cycle components' costs and sustainability.
- Development of a decision support system using the Analytical Hierarchy Process (AHP) and the Multi Attribute Utility Theory (MAUT) based on experts and decision maker's opinions.
- Integrating sustainability and LCC by combining environmental impact costs with future costs in cash flow analysis.
- Developing LCC Forecasting Models for conventional and sustainable school buildings using various approaches: deterministic and stochastic.
- Developing of an integrated Sustainability Assessment Model that incorporates LCA into the LEED rating system.
- Establishing a database of life cycle components' costs and sustainability principles for conventional and sustainable school buildings in North America.
- Developing regression forecasting models to enable school boards to compute the initial costs of their new conventional school buildings based on their structure and exposure types.
- Addressing the probable associated uncertainties by applying stochastic or probabilistic approaches which are influenced by the required confidence levels.

- Enhancing the process of identifying the most attractive alternative by integrating the deterministic and stochastic approaches with risk assessment using the Efficient Frontier method.
- Evaluating each life cycle components' costs and determined their importance (relative weights) and preference ranges of criteria (utilities graph equations) based on experts' and decision makers' opinions.
- Developing LCC Forecasting and Selection Framework software to assist decision makers in school boards in computing their expenditures according to their preferred approach, deterministic or stochastic. This software is user friendly and was designed to accommodate user changes, such as: weights of criteria, utility preference equations, prices of utilities such as gas, electricity, and carbon dioxide, study period, city in North America, year of construction, and expected life span.

8.3 Limitations

The developed LCC Forecasting Models, Sustainability Assessment Model, and Selection Framework are limited to school buildings in Canada, and more particularly, in Quebec.

- Low-rise school buildings (1-4 floors) are the only options.
- The results are based on case-study specified information such as, elementary school, 2 floors, in Montreal, built in 2011, study period of 20 years.

- Crystal Ball software requires at least 15 data points, which was not possible for each alternative.
- There are a limited number of LEED certified schools.
- Most of the cost data is embedded in the model as a triangular probability distribution only.
- The system is limited to the predefined common alternatives for conventional and sustainable buildings.
- Users are asked to use simulation software, such as Crystal Ball, in which case they must select the distribution and the data can then be transferred to the developed software.
- The system assumes that the alternatives have finite life spans according to their structure and exposure types.

8.4 Recommendations for Future Research Work

8.4.1 Research Enhancements

- The collection of additional data points for life cycle components such as initial costs of conventional schools, energy costs, operating and maintenance costs, using other probability distribution functions (i.e. Beta, Lognormal, Normal, etc….).
- Gathering additional experts' opinions regarding the weighting of selection criteria and the preferred range of each criterion.

- Addressing the correlation or impact of each additional LEED point on initial costs and other LCC components with regards to structure and exposure type.

8.4.2 Research Extensions

- Develop a selection framework based on fuzzy LCC models, one that takes fuzzy variables in life cycle components costs into consideration.
- Apply the developed selection framework, LCC forecasting models, and sustainability assessment model on other types of buildings and other civil infrastructures.
- Collect more data for school buildings and add them to the established database of conventional and sustainable school buildings, including observing the future major repair costs for the same buildings.
- Conduct more research on LEED certified buildings and investigate their operating and maintenance costs, major repairs, salvage values, and their expected useful life.
- Make it possible to select structure and envelope types by applying an optimization based simulation.

Abramson, P., “16th Annual – the 2011 School Construction Report”, 2011, School and Planning Management in United States, Available Online at: www.planning4 education.com, Accessed [12 DEC 2011].

AEDG-K12, “Advanced Energy Design Guide for K-12 School Buildings: Achieving 30% Energy Savings Over ANSI/ASHRAE/IESNA Standard 90.1-1999”, 2008, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia, USA

Agron, J., “37th Annual Maintenance and Operations Cost Study”, April 2008, M&O expenditures per student and per square foot for the 2007-08 school year, American School and University.

Al-busaad, S. A., “Assessment of Application of Life Cycle Cost on Construction Projects”, October 1997, Master of Science Thesis in Construction Engineering and Management, King Fahd University of Petroleum and Minerals, Dhahran, Kingdom of Saudi Arabia.

Alkass, S. “Building Economics”, Bldg 6561, September 2007, Class note book, Series of lecture at Department of Building, Civil and Environmental Engineering, Concordia University, Montreal , Canada.

Alkass, S., “LCC comparisons in Various LEED Levels of Certification”, 2008, Study in Building Economics, Bldg 6561, at Department of Building, Civil and Environmental Engineering, Concordia University, Montreal , Canada.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), “Advanced Energy Design Guide for K-12 School Buildings-Achieving 30% Energy Savings toward a Net Zero Energy Building”, 2008, ISBN: 978-1-933742-21-2., USA.

ASHRAE (1999). ANSI/ASHRAE/IESNA Standard 90.1-1999 Energy Standard for Buildings except Low-Rise Residential Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, Georgia, 1999.

ASHRAE (2004). ANSI/ASHRAE/IESNA Standard 90.1-2004 Energy Standard for Buildings except Low-Rise Residential Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, Georgia, 2004.

Ashworth, A., “Cost Studies of Buildings”, Second Edition, 1994, by Longman Group Limited, Malaysia, ISBN 0-582-22873-5.

ASLLC, Advantage Software LLC, “Depreciation - Depreciation Real Estate”, 2011, available online at: http://www.invest-2win.com/depreciation.html, accessed [22 APR 2011].

Assaf, S., Al-Hammad, A., Jannadi, O. A., Abu Saad, S., “Assessment of the problems of application of life cycle costing in construction projects” Cost Engineering Morgantown :Feb 2002. Vol. 44, Iss. 2, p. 17-22 (6 pp.)

Assefa, G., Glaumann, M., Malmqvist, T., Kindembe, B., Hult, H. M., and Eriksson, O., “Environmental assessment of building properties- Where natural and social sciences meet: The case of EcoEffect. Building and Environment”, (2007), 42, 1458-1464.

ASTM, “Standard Practice for Life-Cycle Cost Analysis of Corrugated Metal Pipe Used for Culverts, Storm Sewers, and Other Buried Conduits”, A930 – 03, 2003 [online] available from: http://www.astm.org/Standards/A930.htm [accessed 2 Apr 2009], DOI: 10.1520/A0930-03.

American School and University ASU (2006),”32nd Annual Official Education Construction Report”. May, 2006. Available online: http://asumag.com/ar/605asu21.pdf.

Athena Sustainable Materials Institute, “ATHENA® -The Impact Estimator for Buildings”, 2011, [online] available from: http://www.athenasmi.org/tools/impactEstimator/ index. html [accessed 2 Apr 2011],

ASTM, “Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems”, E917 - 05e1, 2005 [online] available from: http://www.astm.org/Standards/E917.htm [accessed 2 Apr 2009], DOI: 10.1520/E0917-05E01.

Attalla, M., and Yousefi, S., “Constructing Sustainable Buildings: Challenges with Construction Methodologies”, 2009, 2nd International/ 8th Construction Specialty Conference, ICS-053, Canadian Society of Civil Engineering St. John’s, Newfoundland, Canada.

Baker, D., Bridges, D., Hunter, R., Johnson, G., Krupa, J., Murphy, J., and Sorenson K., “Guidebook to Decision-Making Methods”, Dec 2001, Developed for the Department of Energy in United States of America, WSRC-IM-2002-00002.

Bakis, N., Kagiouglou, M., Aouad, G., Amaratunga, Kishk, D. M., and Al-Hajj, A., “An Integrated Environment for Life Cycle Costing In Construction”, 2003, Construction informatics digital library, paper w78-2003-15, [Online] available from:http://itc.scix.net/ [accessed 2009].

Breierova, L. and Choudhari, K., "An Introduction to Sensitivity Analysis", 2001, Prepared for the MIT System Dynamics in Education Project, Massachusetts Institute of Technology, Massachusetts, USA.

Best R., Langston C., and Valence, G., "Work Place Strategies and Facilities Management", Building in Value, First Edition, 2003, Butterworth-Heinemann, ISBN: 0 7506 51504.

Boussabaine H. A., and Kirkham R. J., "Whole Life-Cycle Costing Risk and Risk Responses", First Edition, 2004, by Blackwell publishing Ltd., United Kingdom, ISBN 1-4051-0786-3.

Browning, D. W., and Frej, A. B., "Green Office Building: A Practical Guide to Development", First Edition, 2005, published by ULI, Washington D.C., USA, ISBN: 0874209374.

Bruno Cote, Director of Equipment Services at Lester B. Pearson School Board. Location, "Costs of School Buildings", 2011, Interview with Expert in Area; Industry: Civil Engineering, Montreal, Canada.

Buckely, M., Halsall, R., Vollering, B., Webber, D., "Considering Sustainability in the Selection of Structural Systems, 2004, Environmental Impacts of Structural Steel vs. Cast-in-Place Concrete at Queens University – Integrated Learning Centre.

Canadian Green Building Council, (CaGBC), 2006, available online at: http://www.cagbc.org/cagbc/index.htm, accessed [29 December, 2008].

Cement Association of Canada, "Concrete Thinking for Sustainable Future: Guide to Sustainable Design with Concrete", Version 2, 2007.

Clements-Croome, D., "Intelligent Buildings Design, Management and Operation", First Edition, 2004, Published by Thomas Telford, London, England, ISBN: 9780727732668.

Contributors, W., "Regression analysis", Wikipedia, The Free Encyclopedia, 6 January 2010, http://en.wikipedia.org/w/index.php?title=Regression_analysis &oldid=336206550, [accessed 6 January 2010].

Crawley, D. and Aho, I., "Building Environmental Assessment Methods: Application and Development Trends", 1999, Building Research and Information, 27 (4/5), 300–308.

Crawley, D. B., Hand J. W., Kummert, M., and Griffith, B. T., “Contrasting the Capabilities of Building Energy Performance Simulation Programs”, 2005, U S Department of Energy, Washington, DC, USA.

Christian, J. and A. Pandeya, , “Cost predictions of facilities”. 1997, Journal of Management in Engineering 13(1):52-61

Christian, J. T., Labrecque, M., Newton, L. (1998). Life cycle costs of the barrack block: Are we building better and smarter?. Proceedings, Annual Conference - Canadian Society for Civil Engineering, 1, 129 - 138

Das, S. “Development of Data Base Methodology for Compliance with Regionally Available Mterials Standards of LEED Green Building Rating System”, 2005, Master Thesis of Science, Construction Management Program, Michigan State University, USA

Dell’Isola, A. J., and Kirk, S. J., “Life Cycle Costing for Facilities”, First Edition, 2003, by Reed Construction Data Inc, United States of America, ISBN 0-87629-720-5.

Ding, G. K., “Sustainable Construction- the Role of Environmental Assessment tools”, 2008, Journal of Environmental Management, 86, 451-464.

El-Diraby, T. E. and Rasic, I. “Framework for Managing Life-Cycle Cost of Smart Infrastructure Systems”, 2004, American Society of Civil Engineering, Journal of Computing in Civil Engineering, Volume 18, Issue 2, pp. 115-119.

Eller, S. N. “Benchmarking Community Investments in Green Building and Green Buying Programs in Five U.S Cities”, 2008, Doctoral Thesis, Department of Urban Planning, Portland State University, USA

Elmisalami, T. E., “Developing a Multi Attribute Utility Model for Selecting Information Technologies in the Construction Industry”, 2001, Ph.D. Thesis, Iowa State University, USA

EMSB, English Montreal School Board, “Square Footage Energy Consumptions and Costs”, 2011, Montreal, Canada.

Federal Facilities Council, “Sustainable Federal Facilities: A Guide to Integrating Value Engineering, Life-Cycle Costing and Sustainable Development, (Tech.Rep. #142), Washington, DC, National Academy, Availible online at: http://www.wbdg.org/ccb/SUSFFC/fedsus.pdf. accessed on. [10 Nov 2009].

Ferry D.J., and Flanagan, R., “Life Cycle Costing – A Radical Approach”, 1991, Construction Industry Research and Information Association, Report 122, TH 435 F364 1991.

Fisk, W., “Health and Productivity Gains from Better Indoor Environments and their Implications for the U.S. Department of Energy”, 2002.

Flangan, R., Norman G., and Furbur, J. D., “Life Cycle Costing for Construction”, 1983, Report by Quantity Surveyors Division of the RICS, Department of Construction Management, University of Reading.

Flanagan, R., Norman, G., Meadows J., and Robinson G., “Life Cycle Costing Theory and Practice”, First Edition, 1989, by BSP Professional Books, Oxford, United Kingdome, ISBN 0-632-02578-6

Fowler, K. M. and Rauch, E. M., “Sustainable Building Rating Systems”, 2006, Summary, PNNL-15858. Pacific Northwest National Laboratory.

Fretty, P., “Long Term Planning Helps Maximize Maintenance”, 2003, PEM, 27:33.

Fretwell, P. L.,” The Design of A System for The Implementation of Life Cycle Costing for Educational Buildings in Alabama”,1984, Educat.D. Dissertation, Auburn University, United States – Alabama, Publication No. AAT8505246.

Glazebrook, B., Lanfield, A., and Lloyd, S., “Integrating LCA into Green Building Design”, 2005, Progress Report on Life Cycle Assessment, Building Design and Construction.

Glick, S., “Life Cycle Assessment and Life Cycle Costs: A frame Work with Case Study Implementation Focusing in Residential Heating Systems”, 2007, Doctoral Thesis, School of Education, Colorado State University, Fort Collins, USA.

Glover, J., White, D. O., and Langrish, T. A. G. “Wood Versus Concrete and steel in house construction - A Life Cycle Assessment”, 2002, Journal of forestry, Volume 100, pp. 34-41(8).

Goodwin, P. and Wright G., “Decision Analysis for Management Judgment”, 2004, Third Edition, Published by John Wiley & Sons Ltd, England, ISBN 0-470-86108-8.

Government of Canada, “Statistics Canada”, available online: http://www40.statcan.gc.ca/l01/cst01/manuf05-eng.htm, Accessed on [28 Oct. 2009].

Government of Canada, “Natural Resources Canada”, Available online: http://oee.nrcan.gc.ca/english/index.cfm?attr=4, Accessed on [14 Oct. 2009]

Government of Canada, “Sector Sustainability Tables”, Available online: http://www.sst.gc.ca/, Accessed on [5 Nov.2009]

GreenBuildings.com, “Green Buildings: LEED to Include Building's Lifecycle in Evaluations”, June 7, 2007, available online at: http://greenbuildings.com /news_detail.cfm?newsID=34592, accessed [1 Dec, 2009].

Guggemos, A. A., and Horvath, A., “Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings”, 2005, Journal of Infrastructure Systems ASCE DOI: 10.1061/(ASCE)1076-0342(2005)11:2(93)

Haddad, S., “Economic Impacts of Building Materials on the Environment” FEB 2008, Doctoral Thesis, Department of Building, Civil and Environmental Engineering, Concordia University (Supervision of Dr. S. Alkass).[Online] available from: http://library.concordia.ca [accessed 2009]

Han, W. J., and Tsay, W.D., “Formulation of Quality Strategy Using Analytic Hierarchy Process”, 1998, Twenty Seven Annual Meeting of the Western Decision Science Institute, University of Northern Colorado, USA, pp. 580–583.

Hanby, T. N., “Assessing Barriers to LEED Certification in Oregon” December 2004, Master Thesis in Architecture, Department of Architecture, University of Oregon, USA

Harris, D. J. “A quantitative Approach to The Assessment of The Environmental Impact of Building Materials”, 1999, Building and Environment Journal, 34, 751-758.

Hathaway, W., Hargreaves J., Thompson, G., and Novitsky, D., “A Study into the Effects of Light on Children of Elementary School Age – a Case of Daylight Robbery”,1992, Alberta, Canada

Haviland, D. S., “Life Cycle Cost Analysis 2, using it In Practice”, First Edition, 1978, by The American Institutes of Architects, United States of America, ISBN 0-913962-07-4

Henry, N. W., “R-square and Standardization in Regression”, March 2001, available online at; http://www.people.vcu.edu/~nhenry/Rsq.htm, [accessed 06 JAN 2010].

Heschong Mahone Group, “Daylighting in Schools: an Investigation into the Relationship between Daylighting and Human Performance”, 1999, California, USA.

Heschong Mahone Group, “Windows and Classrooms: a Study of Student Performance and the Indoor Environment”, 2003, California, USA.

Heschong Mahone Group, “Windows and Offices: a Study of Office Worker Performance and the Indoor Environment”, 2003, California, USA.
Hirsch, J., J., “eQUEST 3.64 - the Quick Energy Simulation Tool”, 2010, DOE2 department of energy, Available online at : http://www.doe2.com/equest/, accessed [11 Nov 2010].

Indian Health Services (IHS), "LEED cost evaluation study", Aug 2006, Division of Engineering Services, Department of Health and Human Services Rockville, MD, The workgroup includes six professionals from Seattle.

International Organization for Standardization, ISO 14040, “Environmental Management - Life Cycle Assessment - Principles and Framework”, 2006, Geneva, Switzerland.

International Organization for Standardization, ISO 14044, “Environmental Management - Life Cycle Assessment – Requirements and Guidelines”, 2006, Geneva, Switzerland.

InvestorCraft, “Using the Efficient Frontier Tool”, 2011, [Online] available from: http://www.investorcraft.com/InvestorEducation/EfficientFrontierGuide.aspx [accessed 23 Spt. 2011]

Issa, M.H., Attalla, M., Rankin, J.H., and Christian, A. J., “A Methodology to Investigate Different Usage Aspects in Toronto Schools”, 2009, 2nd International/ 8th Construction Specialty Conference, ICS-048, Canadian Society of Civil Engineering St. John’s, Newfoundland, Canada.

Issa, M.H., Attalla, M., Rankin, J.H., and Christian, A. J., “Evaluating the Long-Term Cost Effectiveness of LEED Canadian Schools”, 2011, 3rd International/ 9th Construction Specialty Conference, CN-152, Canadian Society of Civil Engineering Ottawa, Ontario, Canada.

Jrade, A., “Integrated Conceptual Cost Estimating and Life Cycle Costing System for Building Projects” SEP 2004, Doctoral Thesis, Department of Building, Civil and Environmental Engineering, Concordia University (Supervision of Dr. S. Alkass).[Online] available from: http://library.concordia.ca [accessed 2009]

Kahrman, G., Ruan, D., & Tolga, E., “Capital Budgeting Techniques Using Dicounted Fuzzy Versus Probabilistic Cash Flows”, 2002, information science journal, 142, 1-4.

Kats, G., Alevantis, L., Berman, A., Mills, E., Perlman, J., "The Costs and Financial Benefits of Green Buildings", 2003, Sustainable Building Task Force, Capital E, California, USA

Kats, G., "Greening America's Schools, Cost and Benefits", October 2006, Capital E, California, USA, Available Online at: www.cap-e.com, access online [20 Oct 2008].

Khanduri, A. C., Bedard, C., and Alkass, S., "Assessing Office Building Life Cycle Costs at Preliminary Design Stage", 1996, Structural Engineering Review, 8: 105 - 114.

Kibert, C. J. "Sustainable Construction: Green Building Design and delivery" First Edition, 2005, published by John Wiley & Sons Inc., Hoboken, New Jersey, USA, ISBN:978-0-471-66113-9.

Kibert, C. J., "Sustainable Construction: Green Building Design and delivery" Second Edition, 2008, published by John Wiley & Sons Inc., Hoboken, New Jersey, USA, ISBN:978-0-470-11421-6.

Kirk, S. J., and Dell'Isola A. J., "Life Cycle Costing for Design Professionals", Second Edition, 1995, by McGraw-Hill Inc., United States of America, ISBN 0-07-034804-9.

Kutner, M. Neter, J. Nachtsheim, C & Wasserman, W., "Applied Linear Statistical Models", 2005, 5th Edition, McGraw-Hill Companies Inc. USA

Li, Zhuguo, "A new life cycle impact assessment approach for buildings", 2006, Buildings and Environment journals, Volume 41, Issue 10, October 2006, Pages 1414-1422.

Lippke, B., Wilson, J., Perez-Garcia, J., Bowyer J., and Meil J., "Life-Cycle Environmental Performance of Renewable Building Materials, 2004, Consortium for Research on Renewable Industrial Materials (CORRIM), Forest Products Journal Vol. 54, No. 6

Lisowski, J., "Using the LEED Green Building Rating System for Small to Medium Enterprises", March 2006, Master of Arts in Environment and Management, School of Environment and Sustainability, Royal Roads University, Canada

Liu, Y. "A forecasting Model for Maintenance and Repair Cost for Office Building", September 2006, M.SC. Thesis, Department of Building, Civil and Environmental Engineering, Concordia University (Supervision of Dr. S. Alkass). Available Online from: http://library.concordia.ca [accessed 15 Apr 2009]

Los Angeles School Districts, “Major Repairs Costs Data for School Buildings in Los Angeles City”, 2011. Available online at: http://notebook.lausd.net/portal/page?_ pageid =33,47493&_dad=ptl&_schema=PTL_EP, accessed [05 Jan 2011]

LBPSB, Lester B. Pearson School Board, “Operating and Maintenance Costs of Elementary and High School Buildings”, 2011, English School Boards Association, Montreal, Quebec Canada.

Maciha, J. C., “Preventive Maintenance Guidelines for School Facilities”, 2000, RS Means, Reed construction data, Inc. Construction Publishers and Consultants, USA, ISBN 978-0-87629-579-3.

Mago, S., “Impact of LEED – NC Projects on Constructors and Construction Management Practices”, 2007, Master of Science Thesis, Department of Construction Management, Michigan State University, USA

Malczewski, J., “GIS and Multicriteria Decision Analysis”, 1999, New York, Chichester, Weinheim: John Wiley & Sons, USA, ISBN: 0-471-32944-4.

Malin, N., “Case Study Revist: Thomas L. Wells Public School” , 2012, Green sources, The magazine of Sustainable Design, available online at: http://greensource. .construction .com/green_building_projects, Accessed [14 Jan 2012]

Matthiessen, L. F. and Morris, P. “Costing Green: A Comprehensive Cost Database and Budgeting Methodology”, 2004, Davis Langdon, USA, available online at: https://www.usgbc.org/Docs/Resources/Cost_of_Green_Full.pdf, Accessed on [12 Dec 2009].

Mcdonald, R. C., “The Economics in Green Building in Canada: Highlighting Seven Keys to Cost Effective Green Building”, April 2005, Master of Arts in Environment and Management, Science, Technology, and Environment Devision, Royal Roads University, Canada

Mearig, T., Coffee, N., and Morgan, M. “Life Cycle Cost Analysis Handbook”, State of Alaska - Department of Education & Early Development Education Support Services / Facilities, 1st edition, 1999, [online] available from:

Mer’eb, M. M., “A Tool to Assess The Sustainability of A Building’s Life Cycle at The Conceptual Design Phase”, May 2008, Doctoral thesis, Department of Civil and Environmental Engineering, Cleveland State University, Cleveland, Ohio State, USA.

Medgar, M. L., and M. G. VanGeem, “Comparison of the Life Cycle Assessments of an Insulating Concrete Form House and a Wood Frame House”, 2006, Journal of ASTM International, Vol. 3, No. 9, Paper ID JAI13637 http://www.eed.state.ak.us/facilities/publications/LCCAHandbook1999.pdf [accessed 2 Apr 2009]

Milton, D., Glencross, P., and Walters, M., “Risk of Sick Leave due Associated with Outdoor Air Supply Rate”, 2000, Humidification, and Occupant Complaints.

Minitab Statistical Software Features, “Minitab Software for Statistics, Process Improvement ,Minitab” 2011, available online at: http://www.minitab.com/en-/minitab/features/>, accessed [21 Apr 2011].

Mj3.com, “Investing Fool's Tool #3: (Deficient) Efficient Frontier Analysis- An investing sales gimmick, not an investing tool”, 2011, available online https://www.usgbc at: Org /Docs/Resources/Cost_of_Green_Full.pdf, Accessed on [12 Oct 2011].

Mohan, Satish B. and Loeffert, Benjamin, “Economic of Green Buildings”, 2011, 3rd International/9th Construction Specialty Conference, CSCE, Canadian Society of Civil Engineering, Ottawa, Ontario, Canada, June 14-17, 2011

Moussatche, H., and Languell, J., “Floor Materials Life – Costing for Educational Facilities”, 2001, Volume 19. Number10. pp. 333-343, MCB University Press, ISSN 0263-2772

Natural Resources Canada’s, Office of Energy Efficiency, “Commercial and Institutional Consumption of Energy Survey”, June 2007, Summary Report, ISBN: 978-0-662-49977-0.

NCES, National Center for Educational Statistics, “Functional Age of Schools: Condition and Plans for Improvement- Determining the Age of Public Schools”, 2000, available online at: http://nces.ed.gov/surveys/frss/publications/2000032/index.asp?sectionid=7, accessed [07 MAR 2011].

NECB, National Energy Code of Canada for Buildings, “Insulation of Bbuilding Envelope: Minimum Requirements for Commercial Buildings in City of Montreal’, 1997.

Neter, J., Kutner, M., Nachtsheim, C., William, W., “Applied Linear Statistical Models: Simple Linear Regression”, Fourth Edition, 1996, McGraw-Hill/Irwin, ISBN-13: 978-0256117363.

Newman, D. G., Whittaker, J., Eschenbach, T. G., and Lavelle, J. P, “Engineering Economic Analysis”, Canadian Edition, 2006, by Oxford University press Canada, ISBN-13:978-0-19-541925-2.

New York School Districts, “Major Repairs Costs Data for School Buildings in New York State”, 2005. Available online at: http://schools.nyc.gov/default.htm, accessed [20 July 2010]
Peoples Gas, Natural Gas Delivery, “Managing Energy Costs in, Available online at: http://www.peoplesgasdelivery.com/default.aspx, Accessed [10 Nov 2009]

Pless, S.; Torcellini, P.; Long, N. (2007). Technical Support Document: Development of the Advanced Energy Design Guide for K-12 Schools—30% Energy Savings. Golden, CO: National Renewable Energy Laboratory, NREL/TP-550-42114

Plympton, P., Brown, J., and Stevens, K., “High Performance Schools: Affordable Green Design for K-12 Schools”, Aug 2004, National Renewable Energy Laboratory, Conference Paper, Colorado, USA, NREL/CP – 710 – 34967.

PointCarbon, Carbon Trade Market, “Carbon Dioxide (CO_2) Maket Price”, 2011, Available online at: http://www.pointcarbon.com/, Accessed [25 June 2011]

Reed Construction Data Inc., RSMeans, “RSMeans Construction Square Foot Cost calculator”, 2011, available online at: http://rsmeans.reedconstructiondata.com/Means CostWorks.aspx, Accessed on [11 FEB 2011].

Saaty, T. L. “The Analytic Herarchy Process: Planning, Priority Setting, Resources Allocation”, 1980, St. Louis, San Francisco, McGraw - Hill, New York, USA.

Saaty, Thomas L. (2008-06). "Relative Measurement and its Generalization in Decision Making: Why Pairwise Comparisons are Central in Mathematics for the Measurement of Intangible Factors - The Analytic Hierarchy/Network Process". RACSAM (Review of the Royal Spanish Academy of Sciences, Series A, Mathematics) 102 (2): 251–318. http://www.rac.es/ficheros/doc/00576.PDF. Retrieved 2008-12-22.

Salem, O., Abou Rizk, S., and Ariaratnam, S., “Risk-based Life Cycle Costing of Infrastructure Rehabilitation and Construction Alternatives”, 2003, American Society of Civil Engineering, Journal of Infrastructure System. Volume 9, Issue 1, pp. 6-15

Shahata, K. “Stochastic Life Cycle Cost Modeling Approach for water Mains”, March 2006, Master thesis, Department of Building, Civil, and Environmental Engineering, Concordia University, Montreal, Canada.

Siddiqi, K.M., Chatman, D., and Cook, G. “Role of education and industry towards more sustainable construction”, 2008, International Journal of Environmental Technology and Management, 8(2-3): 310-21.

Sinou, M., and Kyvelou, S., “Present and future of building performance assessment tools”, 2006, Management and Environmental Quality: An International Journal, 17(5), 570-586.

Sonnemann, G., Castells, F., and Schuhmacher, M., “Integrated Life Cycle and Risk Assessment for Industrial Processes, Advanced Methods in Resource and Waste Management”, First Edition, 2004, Lewis Publishers, New York, USA, ISBN 1-56670-644-0.

SPM (2007). School Planning and Management 2007 Construction Report. www.peterli.com/global/pdfs/SPMConstruction2007.pdf Last Accessed May 2007.

Studio4, LLC, “LEED Green Associate Study Guide- A Study Resource for Green Building and LEED Core Concepts and the LEED Green Associate Exam Process”, 2009 edition, Addenda: 01 FEB, 2010,

Sullivan, J. G., “Decision Model for Public Sector Assessment of Sustainable Buildings in Florida”, 2007, Doctoral Thesis, School of Building Construction University of Florida, USA.

Sustainable Buildings Industry Council (SBIC). 2004. High Performance Resource and StrategyGuide. Washington, D.C.: Sustainable Buildings Industry Council.

Thurston, D. L., “Multiattribute Utility Analysis of Materials Selection Decisions”, (Ph. D.) Thesis, Massachusetts Institute of Technology, Dept. of Civil Engineering, 1987 by Deborah Lee http://dspace.mit.edu/handle/1721.1/14810

Townsend, P. and Wagner, C., “Timber as a Building Material - An environmental comparison against synthetic building materials”, 2002, National Association of Forest Industries Ltd.

Trusty, W. B. and Horst, S., “Integrating LCA Tools in Green Building Rating Systems”, 2002, proceedings: USGBC Green building International Conference & Expo. Astin: Building Green, Inc.

United Nations, "Kyoto Protocol - Framework Convention on Climate Change", 2011, available online at: http://unfccc.int/kyoto_protocol/items/2830.php, Accessed [22 Dec 2011].

U.S Department of Energy, "Buildings Energy Data Book", Energy Efficiency and Renewable Energy, 2009, available online http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=1.1.3

U.S. Environmental Protection Agency Green Building Workgroup, "Buildings and the Environment: A Statistical Summary Compiled by", December 2004, Available online http://www.epa.gov/greenbuilding/pubs/gbstats.pdf, Accessed on Nov 10, 2009.

U.S. Environmental Protection Emergency, "Green Building: Definition of Green Building", 2009, available online at: http://www.epa.gov/greenbuilding, Accessed [11 Nov 2009].

USGBC, "Integrating LCA into LEED, Working Group A (Goal and Scope)", 2006a, Interim Report #1, USGBC, USA

USGBC, "Integrating LCA into LEED, Working Group B (LCA Methodology)", 2006b. Interim Report #1, USGBC, USA.

U.S. Green Building Council (USGBC), 2004, Leadership in Energy & Environmental Design (LEED). Available online: www.usgbc.org. Washington, D.C.: U.S. Green Building Council accessed [12 Oct 2009].

U.S. Green Building Council (USGBC), Leadership in Energy & Environmental Design (LEED), "LEED Certified School Buildings in North America", 2010 Available online: www.usgbc.org. Washington, D.C.: U.S. Green Building Council accessed [23 DEC 2010].

Vangen, C. M., "ASP-ASAP Application Service provider", 2001, brief article Buildings 95:47, [Online] available: http://findarticles.com/p/articles/, [accessed 2009].

Victorian Native Forest Timbers, "Timber in Building Construction: Ecological Implications", 1996, The Environmental Impact of Building Materials, Victorian Native Forest Timbers Research Paper commissioned by the Timber Development-Association.

Wedding, G. C., "An Analysis of Variation in the Energy-Related Environmental Impacts of LEED Certified Buildings", 2007, Journal of Green Building, [2(4): pp. 151-170].

Wedding, G. C., “Understanding Sustainability in Real Estate: A Focus in Measuring and Communicating Success in Green Building”, 2008, Doctoral Thesis, Department of Environmental Sciences and Engineering, University of North Carolina, USA

Wedding, G. C., “Improving the Link Between the LEED Green Building Label and A Building’s Energy-Related Environmental Metrics”, 2008, submitted to Journal of Green Building.

Weisberg, H. F., “Analysis of Regression and Surveys in Ohio LSC Report on S.B. 102 on Claimed Cost Savings from Exempting School Construction from Prevailing Wage Requirements”, 2002, Ohio State University, USA.

Wikipedia contributors, “Analytic Hierarchy Process”, Wikipedia, The Free Encyclopedia, 21 December 2009, 13:25 UTC, http://en.wikipedia.org/w/index.php?title=Analytic_Hierarchy_Process&oldid=333 055458> [accessed 23 December 2009].

Zayed, T., Chang, L., Fricker, J., “Life-Cycle Cost Based Maintenance Plan for Steel Bridge Protection Systems”, May 2002, Journal of Performance of Constructed Facilities, American Society of Civil Engineering , Volume 16, Issue 2, pp. 55-62.

Zayed, T & Halpin, D, “Productivity and Cost Regression Models for Pile Construction”, 2005, ASCE Journal of Construction engineering and Management, Volume 131, No 7, July 2005.

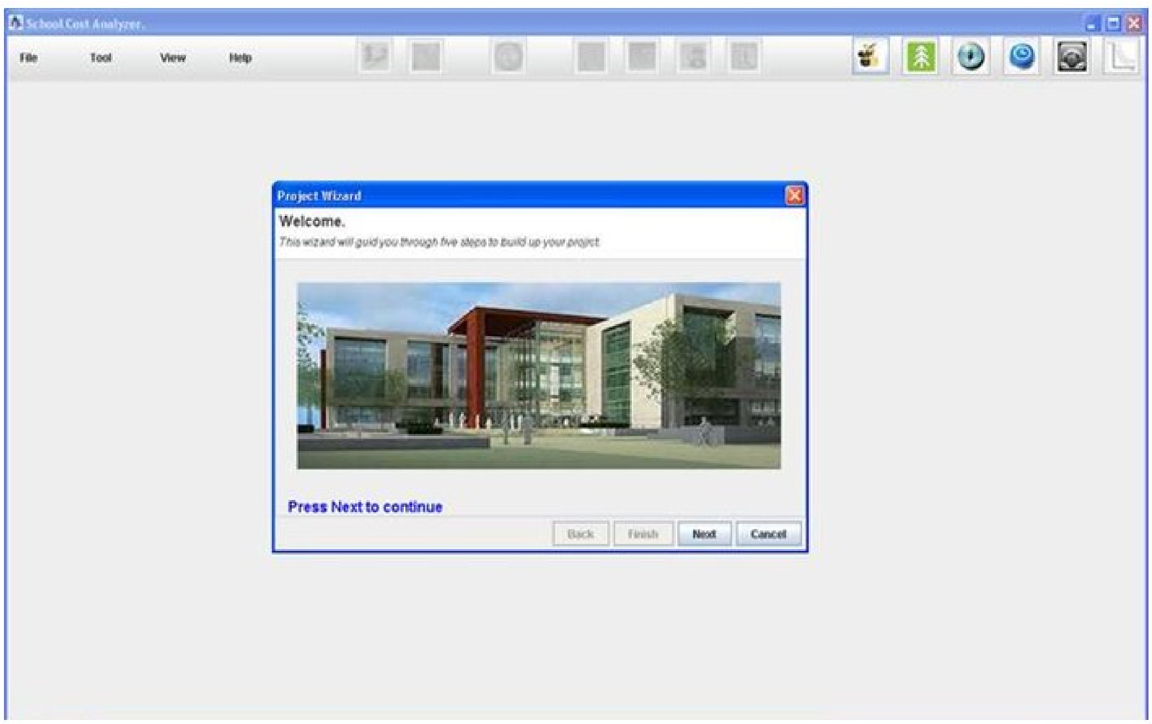
Zhang, K., “Life Cycle Costing for Office buildings in Canada”, 1999, M.SC. Thesis, Department of Building, Civil and Environmental Engineering, Concordia University (Supervision of Dr. S. Alkass), [Online] available from: http://library.concordia.ca [accessed 2 Apr 2009]

Zhang, Z., Wu, X., Yang, X., and Zhu, Y. ‘BEPAS - a life cycle building environmental performance assessment model”. Building and Environment, (2006), 41 669-675.

Zhuguo, L., “A new life cycle impact assessment approach for buildings”, 2006, Buildings and Environment 41,1414-1422. Available online at http://www.sciencedirect.com, doi:10.1016/j.buildenv.2005.05.034

APPENDIX A: Developed LCC and Sustainability Analyzer Software (LCCSCH00I2)

LCCSCH00I2 software was developed in this study to prove the concept and validate the methodology as shown in figure A-1. This software analyzes LCC and sustainability for new school buildings in North America to help decision makers to select the optimum structure and envelope types by applying the developed selection framework. The default settings were set to analyze a new school building in Montreal in 2011, over 20 years of operation.



First of all, the users (decision makers in school boards) are asked to create a new project from the file menu in the main toolbar, and then to identify the school parameters such as school area, school level, and number of floors, as presented in figure A-2.

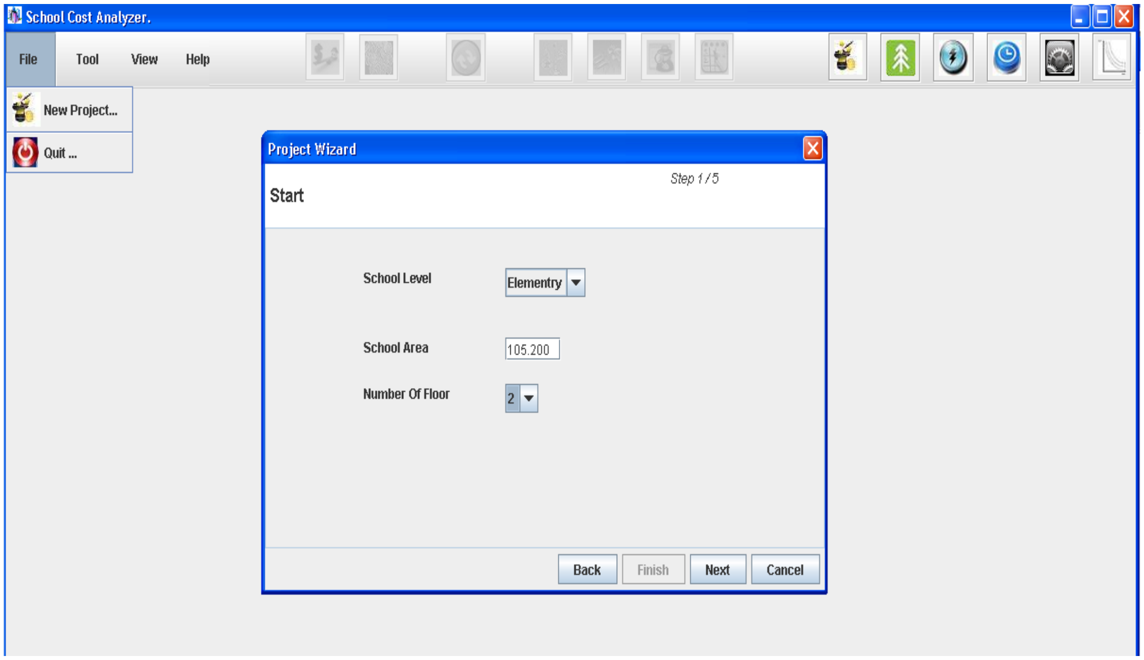


Figure A-2 Identification of new school parameters

In the next step the user is asked to select the alternatives to be investigated and compared in this study. Seven conventional and seven sustainable alternatives are offered in this software, which can be selected separately or together as shown in figure A-3.

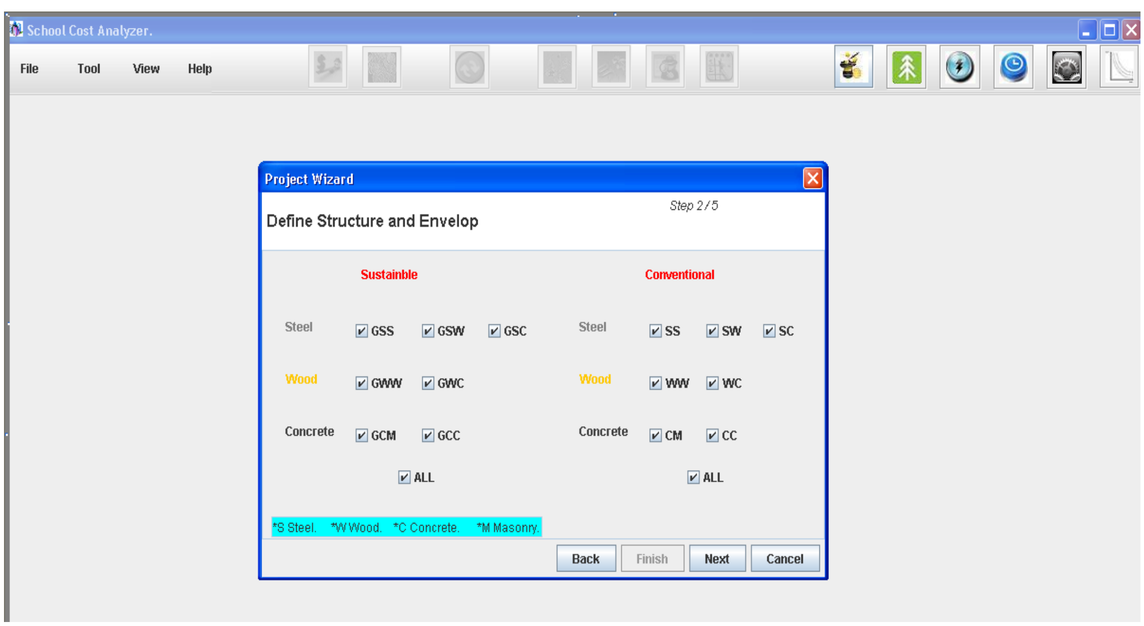


Figure A-3 Defining conventional and sustainable alternatives

Other general parameters, such as city, time, study period, discount and inflation rates, and useful life can be changed by using the 'Setting menu' located in the tool bar and inserting the users' preferences, as shown in figure A-4.

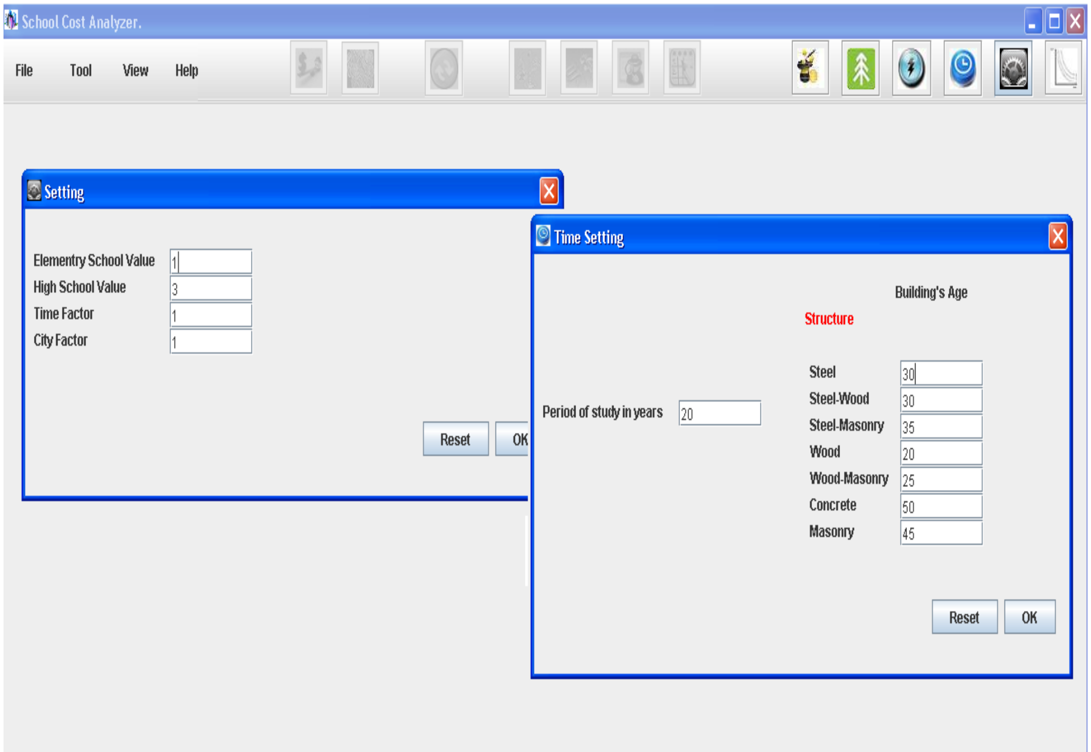


Figure A-4 Adjusting the time, city factors, period of study, and expected age

For the environmental impact cost, the metric tonne price of CO_2 can be adjusted according to the current stock market trading. Also, CO_2 quantification for various alternatives is subject to modification by the city index factors for CO_2 emissions and climate zone indices. Utility rates such as electricity and gas rate also are changeable, since they are subject to r variability as indicated in figure A-5.

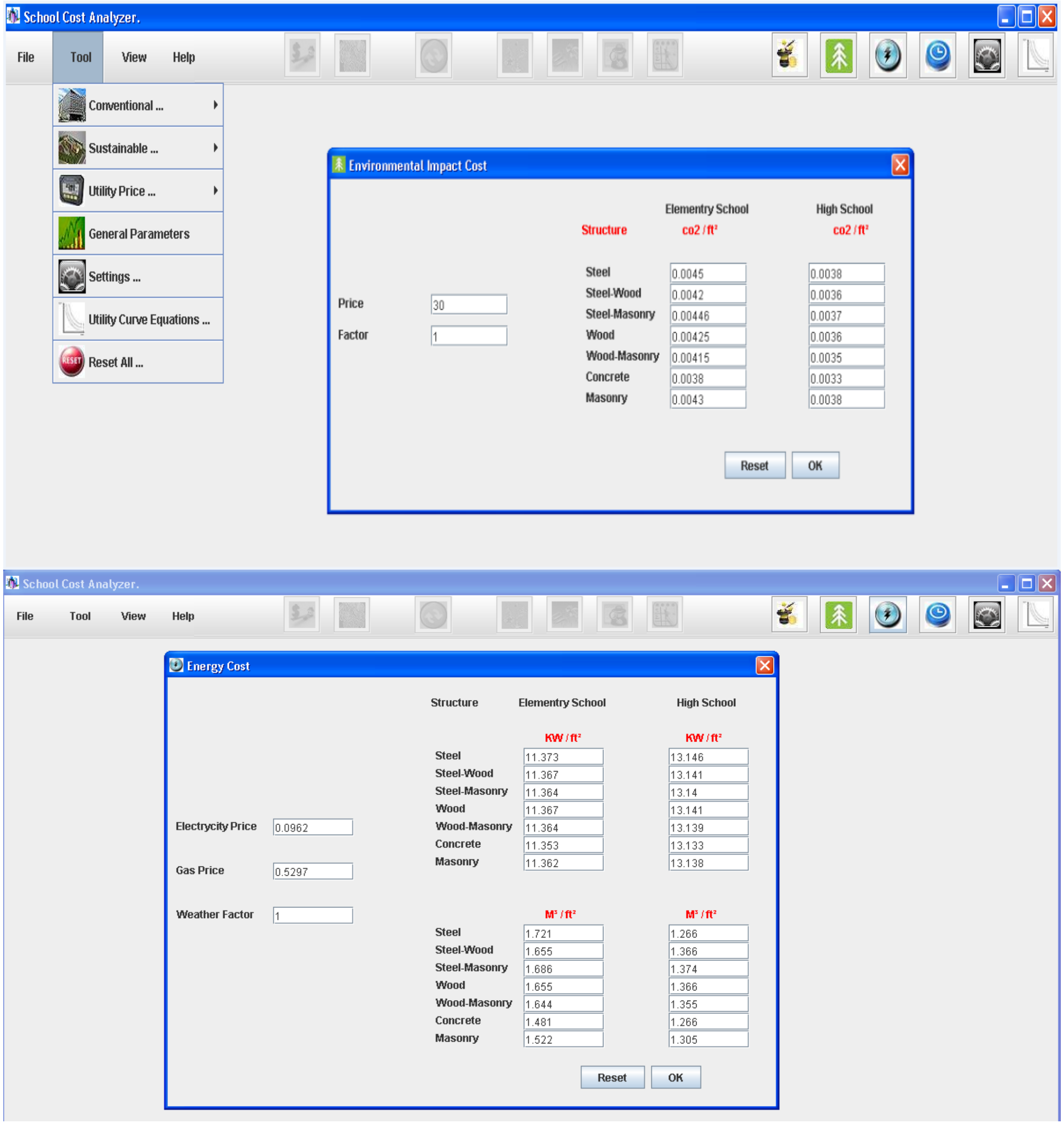


Figure A-5 Adjusting of CO_2 price, energy utilities' rates, and weather factors

In the next stage the user is asked to set weights for the selection criteria if required. The default weights are already assigned based on the experts' opinions, as can be seen in figure A-6. The total weight of the selection criteria is out of 100%.

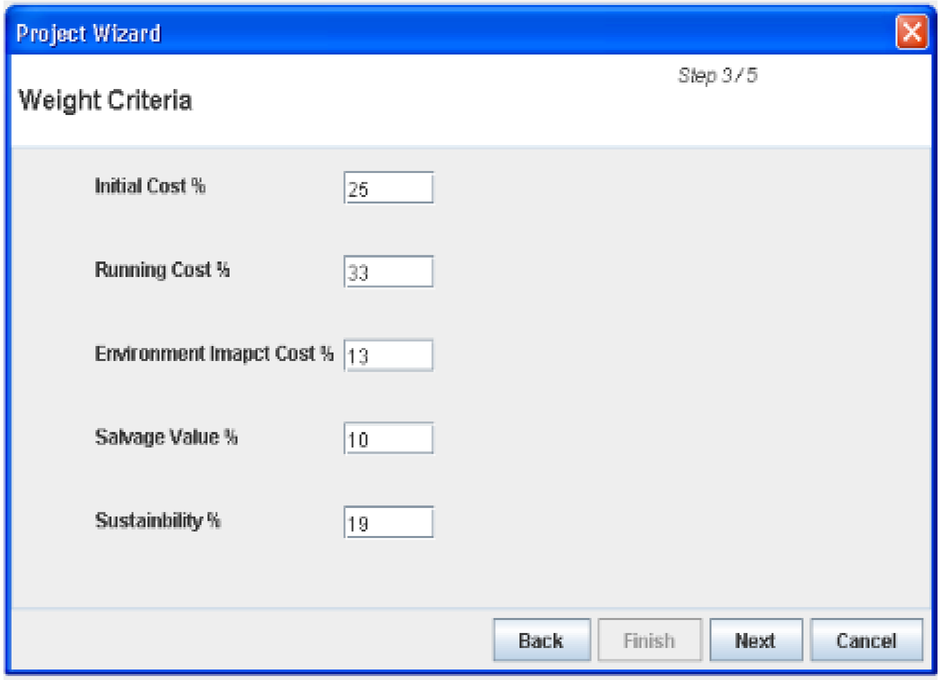


Figure A-6 Setting weights for the selection criteria

In addition, the user is asked to set utility scores for each criterion and to develop utility curves for the various selection criteria. The default utilities curves are built according to the experts' opinions. Any modification in the general parameters causes change in the default or in the developed utility curves, which consequently requires resetting of the utilities curves by the user. The utility score should first be determined for the whole criteria, by filling in the preferred values at all five utility scores. After filling in the preferred values for each criterion, the utility curves will be developed using Microsoft Excel. The coefficients of the resulted utility curve equations should be transferred to the software as shown in figure A-7.

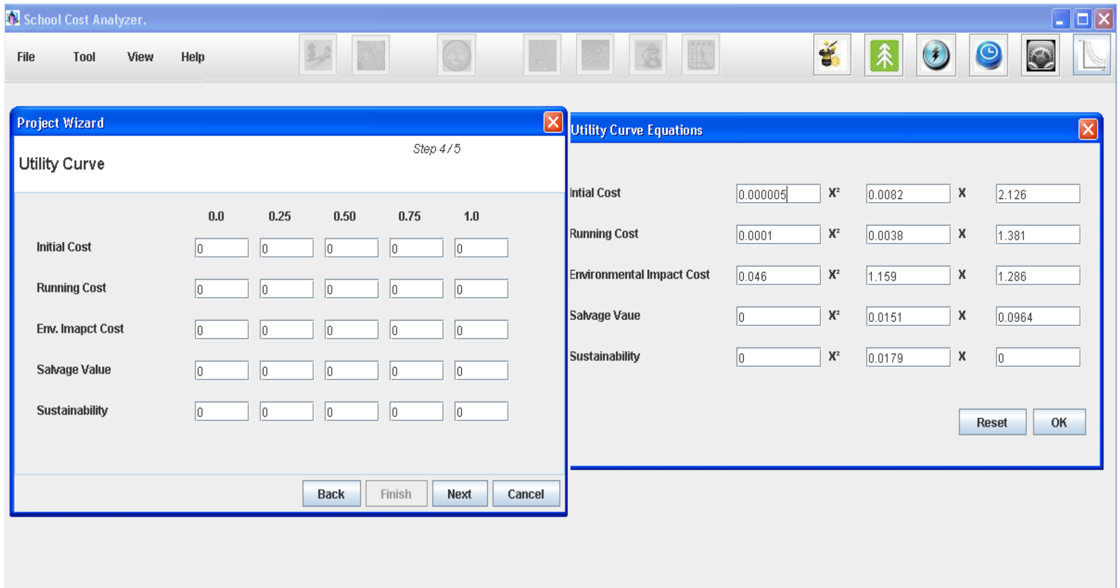


Figure A-7 Setting of utilities scores for selection criteria

In the next step the user is asked to determine the LCC and sustainability calculation approach -- deterministic or stochastic. If the selection is stochastic, the required level of confidence, or acceptable risk level, should be determined as displayed in figure A- 8.

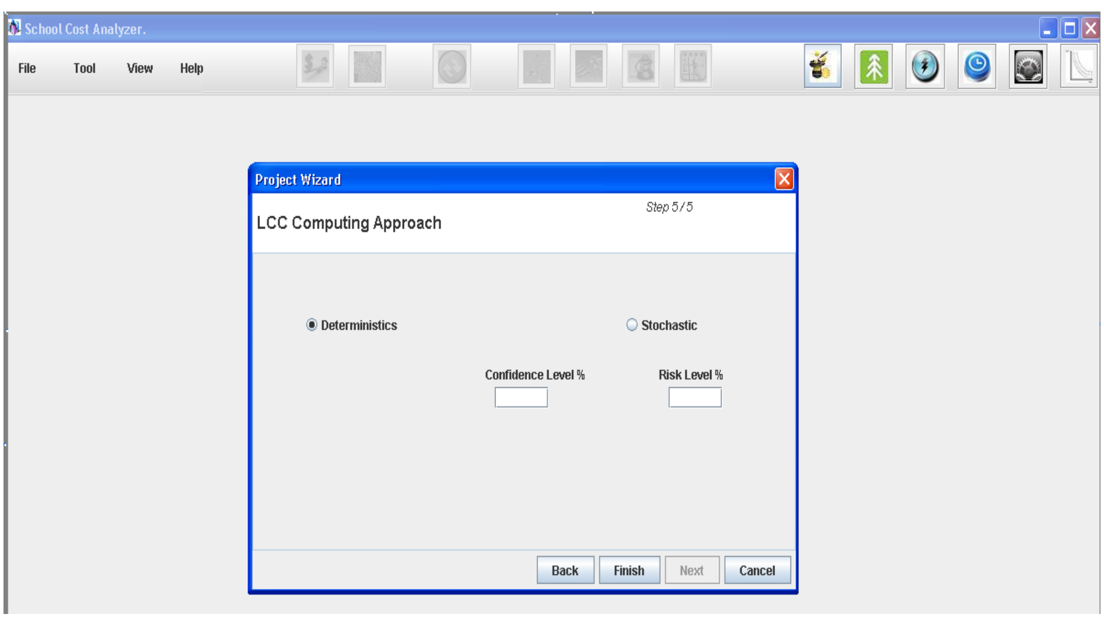
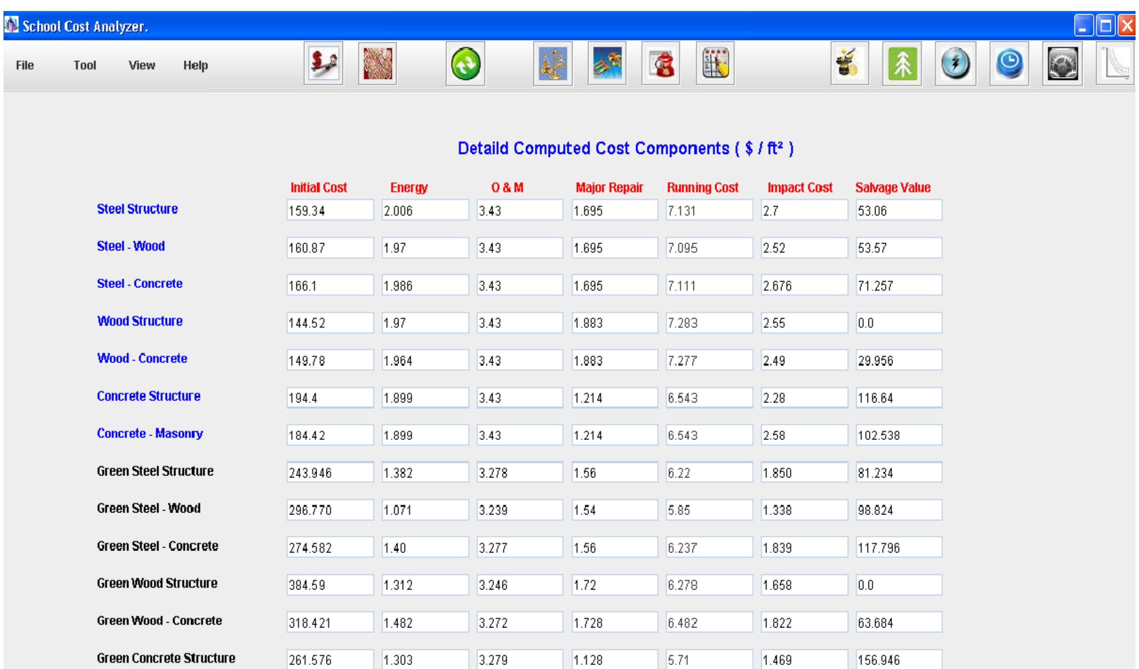


Figure A-8 Determining the computing approach and selection method

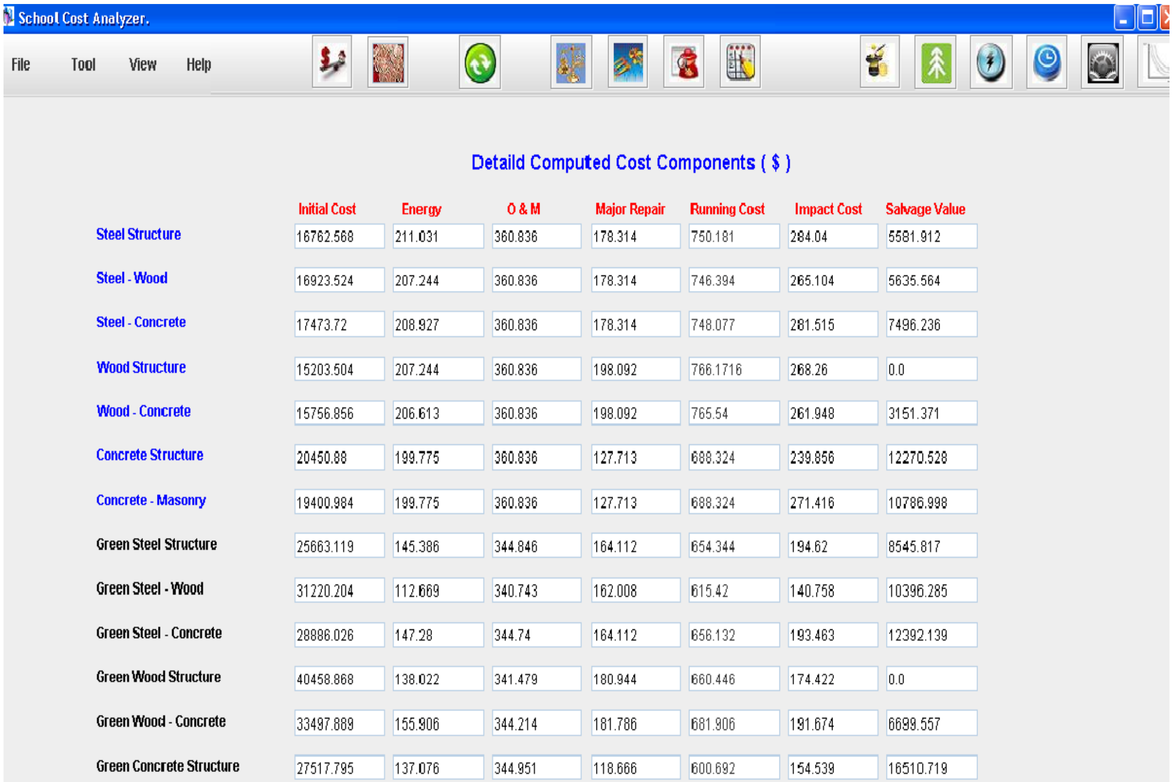
The results of this software are presented for each alternative in detail, for all of the LCC components such as initial costs, energy costs, operating and maintenance costs, major repairs costs, environmental impact costs, and salvage values. The outputs are presented in different formats:

- Detailed costs: present the computed square footages' life cycle components' costs ($/ft^2) according to their time of occurrence, as shown in figure A-9.
- Total cost: presents the total computed life cycle components' costs of the whole building according to their time of occurrence, as shown in figure A-10.
- LCC in NPV ($/ft^2): displays the present value (PV) of the square footages' life cycle components' costs, resulted NPV, and sustainability assessment (in LEED score). This output is used in the selection framework, as presented in figure A-11.



	Initial Cost	Energy	O & M	Major Repair	Running Cost	Impact Cost	Salvage Value
Steel Structure	159.34	2.006	3.43	1.695	7.131	2.7	53.06
Steel - Wood	160.87	1.97	3.43	1.695	7.095	2.52	53.57
Steel - Concrete	166.1	1.986	3.43	1.695	7.111	2.676	71.257
Wood Structure	144.52	1.97	3.43	1.883	7.283	2.55	0.0
Wood - Concrete	149.78	1.964	3.43	1.883	7.277	2.49	29.956
Concrete Structure	194.4	1.899	3.43	1.214	6.543	2.28	116.64
Concrete - Masonry	184.42	1.899	3.43	1.214	6.543	2.58	102.538
Green Steel Structure	243.946	1.382	3.278	1.56	6.22	1.850	81.234
Green Steel - Wood	296.770	1.071	3.239	1.54	5.85	1.338	98.824
Green Steel - Concrete	274.582	1.40	3.277	1.56	6.237	1.839	117.796
Green Wood Structure	384.59	1.312	3.246	1.72	6.278	1.658	0.0
Green Wood - Concrete	318.421	1.482	3.272	1.728	6.482	1.822	63.684
Green Concrete Structure	261.576	1.303	3.279	1.128	5.71	1.469	156.946

Figure A-9 Square footages' life cycle components costs in $/ft^2



Detaild Computed Cost Components ($)

	Initial Cost	Energy	O & M	Major Repair	Running Cost	Impact Cost	Salvage Value
Steel Structure	16762.568	211.031	360.836	178.314	750.181	284.04	5581.912
Steel - Wood	16923.524	207.244	360.836	178.314	746.394	265.104	5635.564
Steel - Concrete	17473.72	208.927	360.836	178.314	748.077	281.515	7496.236
Wood Structure	15203.504	207.244	360.836	198.092	766.1716	268.26	0.0
Wood - Concrete	15756.856	206.613	360.836	198.092	765.54	261.948	3151.371
Concrete Structure	20450.88	199.775	360.836	127.713	688.324	239.856	12270.528
Concrete - Masonry	19400.984	199.775	360.836	127.713	688.324	271.416	10786.998
Green Steel Structure	25663.119	145.386	344.846	164.112	654.344	194.62	8545.817
Green Steel - Wood	31220.204	112.669	340.743	162.008	615.42	140.758	10396.285
Green Steel - Concrete	28886.026	147.28	344.74	164.112	656.132	193.463	12392.139
Green Wood Structure	40458.868	138.022	341.479	180.944	660.446	174.422	0.0
Green Wood - Concrete	33497.889	155.906	344.214	181.786	681.906	191.674	6699.557
Green Concrete Structure	27517.795	137.076	344.951	118.666	600.692	154.539	16510.719

Figure 10A-10 Total life cycle components costs for various alternatives

Life Cycle Cost (LCC) in NPV ($ / ft²)

	Initial Cost	Running Cost	Impact Cost	Salvage Value	Net Present Value	Sustainability Perfromance (Lead Score)
Steel Structure	159.34	104.579	1.018	19.998	-244.939	14
Steel - Wood	160.87	104.051	0.95	20.19	-245.681	15
Steel - Concrete	166.1	104.286	1.009	26.856	-244.538	14
Wood Structure	144.52	106.808	0.961	0.0	-252.289	15
Wood - Concrete	149.78	106.72	0.938	11.29	-246.148	15
Concrete Structure	194.4	95.956	0.859	43.96	-247.255	19
Concrete - Masonry	184.42	95.956	0.972	38.645	-242.703	17
Green Steel Structure	243.946	91.219	0.697	30.616	-305.246	38
Green Steel - Wood	296.770	85.793	0.504	37.246	-345.821	46
Green Steel - Concrete	274.582	91.468	0.693	44.396	-322.347	38
Green Wood Structure	384.59	92.069	0.625	0.0	-477.284	42
Green Wood - Concrete	318.421	95.061	0.687	24.002	-390.167	39
Green Concrete Structure	261.576	83.739	0.554	59.151	-286.718	36

Figure A-11 Square footage life cycle components' costs in PV and LEED score

The results in figure 10 are then plotted in the utility curves by applying the developed utilities equations. The utility scores are then computed for all five selection criteria, as shown in figure A-12.

	25%	33%	13%	10%	19%
	Initial Cost	Running Cost	Impact Cost	Salvage	Sustainability
Steel Structure	0.946	0.685	0.154	0.206	0.251
Steel - Wood	0.936	0.694	0.226	0.208	0.268
Steel - Concrete	0.902	0.69	0.163	0.309	0.251
Wood Structure	1.0	0.646	0.215	0.0	0.268
Wood - Concrete	1.0	0.648	0.239	0.074	0.268
Concrete Structure	0.721	0.825	0.324	0.567	0.34
Concrete - Masonry	0.784	0.825	0.203	0.487	0.304
Green Steel Structure	0.423	0.896	0.501	0.366	0.68
Green Steel - Wood	0.133	0.971	0.714	0.466	0.823
Green Steel - Concrete	0.251	0.892	0.505	0.574	0.68
Green Wood Structure	0.0	0.883	0.58	0.0	0.752
Green Wood - Concrete	0.022	0.839	0.511	0.266	0.698
Green Concrete Structure	0.323	0.998	0.658	0.797	0.644

Figure A -12 Obtained utilities score by various alternatives over selection criteria

The total score is computed for each alternative in each criterion by multiplying the utility score by the relative importance weight of that criterion. Adding up the computed subtotals for all the criteria produces the total score, as displayed in figure 13. The user or decision maker can compare the results and select the most favourable alternative that achieves the highest score.


School Cost Analyzer.

File Tool View Help

Total Obtained Utility Score (Weight Criteria x Utiliy Score)

	Initial Cost (25%)	Running Cost (33%)	Impact Cost (13%)	Salvage (10%)	Sustainability (19%)	Totol
Steel Structure	23.659	22.596	2.0	2.056	4.761	55.071
Steel - Wood	23.407	22.893	2.944	2.085	5.102	56.43
Steel - Concrete	22.548	22.761	2.124	3.091	4.761	55.286
Wood Structure	25.0	21.32	2.791	0.0	5.102	54.213
Wood - Concrete	25.0	21.371	3.111	0.741	5.102	55.325
Concrete Structure	18.022	27.221	4.217	5.674	6.462	61.595
Concrete - Masonry	19.595	27.221	2.638	4.871	5.782	60.107
Green Steel Structure	10.58	29.553	6.507	3.659	12.924	63.222
Green Steel - Wood	3.321	32.042	9.276	4.66	15.645	64.944
Green Steel - Concrete	6.285	29.434	6.564	5.74	12.924	60.946
Green Wood Structure	0.0	29.145	7.535	0.0	14.284	50.964
Green Wood - Concrete	0.548	27.673	6.649	2.66	13.264	50.794
Green Concrete Structure	8.08	32.934	8.554	7.968	12.244	69.779

A-13 Total computed scores for the various alternatives' overall selection criteria

If the user is willing to apply uncertainty, the stochastic approach is applied. This method starts with two basic steps: selecting the probability distribution and defining the required confidence level. The default distributions are selected based on the best fit of the available data. This process will require users to use Crystal Ball software to select the distribution and perform the simulation, applying of Monte Carlo technique. The user is then asked to transfer the output data to the developed software. Once the level of confidence has been determined, the user is asked to run the stochastic system. The result of this approach is presented as the minimum total obtained score.

Finally, the risk assessment process can be applied to enhance the selection of the most attractive alternative based on the most vital criteria.