INTEGRATED LIFE CYCLE SUSTAINABILITY PERFORMANCE ASSESSMENT FRAMEWORK FOR RESIDENTIAL MODULAR BUILDINGS

by

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Abstract

Due to the rapid global growth of sustainable construction strategies, it is important to assess the sustainability of buildings constructed by different methods. In the past few decades, the construction industry has been exposed to the process of industrialization and experimenting off-site construction methods. Modular construction, as the primary method of off-site construction, came into practice as an alternative to conventional on-site construction. This method has been claimed to offer many advantages over conventional construction. However, the continued expansion of modular construction highly depends on the quantification and evaluation of its sustainability and the claimed advantages.

In this research, an integrated life cycle sustainability performance assessment framework for single-family residential modular buildings was developed. To this end, the results of a comprehensive literature review, various methodologies and tools, and extensive data collection, were integrated to develop a multi-level decision support framework (DSF). The overall framework commences with the identification and selection of the most applicable sustainability performance criteria (SPCs) for comparing the performance of modular buildings versus conventional buildings. To develop a sustainability index for each selected SPC, relevant sustainability performance indicators (SPIs and sub-SPIs) have been determined, calculated, and aggregated using suitable multi-criteria decision analysis (MCDA) methods and life cycle assessment (LCA). Subsequently, the same methodology has been used to develop the sustainability indices to represent the performance of a given modular building at higher levels including environmental sustainability, economic sustainability, and overall sustainability. To enable comparisons of the developed indices with the industry's performance benchmarks, suitable sustainability performance scales (SPSs) have been established at the corresponding levels.

This research, which integrated life cycle thinking and decision making, helps the construction industry and governments to make informed decisions on the selection of the most sustainable construction methods by taking into account the regional circumstances. In addition, it assists with identification of the underperforming environmental and economic areas over the life cycle of modular buildings to apply relevant corrective actions on similar projects. Moreover, the methodology outlined in this research can be adopted for sustainability assessment of other practices, processes, or products in the construction filed or any other fields.

Lay Summary

This study involves the promotion of sustainable construction across Canada with the focus on British Columbia. Although modular construction as the primary method of off-site construction has been claimed to offer many sustainability advantages over conventional on-site construction, limited studies were undertaken to quantitatively compare the sustainability of these construction methods. The main contribution of this thesis is to address the research gap by developing a holistic assessment framework by which the life cycle environmental and economic performance of single-family residential modular buildings are compared with the performance benchmarks of conventional buildings. The developed framework is presented in the form of a decision support framework (DSF) and demonstrated through two case study modular buildings. Results of this thesis will assist the construction decision makers, such as governmental organizations and developers, with the selection of optimal construction methods and also identification and improvement of underperforming areas of modular buildings.

Preface

I, Mohammad Kamali, conceived and developed all the contents presented in this thesis under the supervision of Dr. Kasun Hewage. I wrote all the manuscripts from this research work and the doctoral thesis. The research supervisor has reviewed the manuscripts and the thesis and provided critical feedback to improve these documents. In addition, third authors of the three-author articles, Dr. Rehan Sadiq and Dr. Abbas S. Milani, have reviewed the corresponding manuscripts and provided constructive feedback to improve them. Nine journal and three conference articles are currently published, under review, or will be submitted for possible publication, based on the research work presented in this thesis. Details of the aforementioned articles are provided below.

1. A version of Chapter 2 has been published in *Proceedings of the Canadian Society for Civil Engineering International Construction Specialty Conference (6th CSCE/CRC)* entitled "Sustainability performance assessment: A life cycle based framework for modular buildings" (Kamali and Hewage 2017a).
2. A version of Chapter 3 has been published in *Renewable & Sustainable Energy Reviews* entitled "Life cycle performance of modular buildings: A critical review" (Kamali and Hewage 2016).
3. A version of Chapter 4 has been published in *Journal of Cleaner Production* entitled "Development of performance criteria for sustainability evaluation of modular versus conventional construction methods" (Kamali and Hewage 2017b).
4. A version of Chapter 4 has been published in *Proceedings of the Modular and Offsite Construction (MOC15) Summit & 1st International Conference on the Industrialization of Construction (ICIC)* entitled "A framework for comparative evaluation of the life cycle sustainability of modular and conventional buildings" (Kamali and Hewage 2015a)
5. A version of Chapter 4 has been published in *Proceedings of the Canadian Society for Civil Engineering International Construction Specialty Conference (ICSC15)* entitled "Performance indicators for sustainability assessment of buildings" (Kamali and Hewage 2015b).
6. A version of Chapters 5 has been published in *Building and Environment* entitled "Life cycle sustainability performance assessment framework for residential modular buildings: Aggregated sustainability indices" (Kamali et al. 2018).
7. A version of Chapter 5 will be submitted for possible publication in *Sustainable Cities and*

Society entitled "Environmental sustainability benchmarking of modular homes – Part I: Performance quantification" (Kamali et al. 2019a).

8. A version of Chapter 6 will be submitted for possible publication in *Sustainable Cities and Society* entitled "Environmental sustainability benchmarking of modular homes – Part II: Performance assessment" (Kamali et al. 2019b).

9. A version of Chapter 5 will be submitted for possible publication in *Journal of Cleaner Production* entitled "Economic sustainability benchmarking of modular homes – Part I: Performance quantification" (Kamali et al. 2019c).

10. A version of Chapter 6 will be submitted for possible publication in *Journal of Cleaner Production* entitled "Economic sustainability benchmarking of modular homes – Part II: Performance assessment" (Kamali et al. 2019d).

11. A version of Chapter 7 is under review in *Energy and Buildings* entitled "Comparing environmental impacts of different construction methods: Cradle-to-gate LCA for residential buildings in BC, Canada" (Kamali et al. 2019e).

12. A research article consisting of an overall integrated framework developed in this thesis will be submitted for possible publication in *Clean Technologies and Environmental Policy* entitled "Towards sustainable buildings: Conceptualization to implementation of a multi-level decision support framework for off-site versus on-site construction methods" (Kamali and Hewage 2019f).

I secured the approval of UBC's Behavioral Research Ethics Board (UBC BREB No: H14-02361, Project title: Sustainability of Modular Construction) for all the surveys and interviews conducted in this research.

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List of Abbreviations

A	Affordability
AB	Adaptability of Building
ABB	Aesthetic options and Beauty of Building
AFUE	Annual Fuel Utilization Efficiency
AHP	Analytic Hierarchy Process
AL	Air Leakage
AP	Acidification Potential
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
AT	Alternative Transportation
BC	British Columbia
BEES	Building for Environmental and Economic Sustainability
C&D	Construction and demolition waste
CD	Community Disturbance
CHC	Cultural and Heritage Conservation
CI	Consistency Index
CO_2eq	Carbon dioxide equivalents
CR	Consistency Ratio
CWM	Construction Waste Management
DB	Durability of Building
DCC	Design and Construction Costs
DCT	Design and Construction Time
DM	Decision Maker
DSF	Decision Support Framework
EC	End of life Costs
EE	Eco-toxicity Effect
EF	Energy Factor
EIFS	Exterior Insulation Finishing Systems
ELECTRE	Elimination and Choice Translating Reality
EO	Expert Opinions
EP	Energy Performance and efficiency strategies
E-P	Eutrophication Potential
EPA	Environmental Protection Agency
ER	Energy Rating
FFC	Fossil Fuel Consumption
FSC-certified	Forest Stewardship Council certified
FU	Functionality and Usability of the physical space
GE	Greenhouse gas Emissions
GHG	Greenhouse Gases
GWP	Global Warming Potential
HDD	Heating Degree Days
HHE	Human Health Effect
HO	Health, comfort, and well-being of Occupants
HSPF	Heat Seasonal Performance Factor
HVAC	Heating, Ventilation, and Air Conditioning
IECC	International Energy Conservation Code
ILE	Influence on the Local Economy

IM	Integrated Management
IRR	Investment and Related Risks
ISD	Influence on local Social Development
ISO	International Organization for Standardization
ISW	Industrial Solid Waste
LBC	Living Building Challenge
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LEED	Leadership in Energy & Environmental Design
MBI	Modular Building Institute
MC	Maintenance Costs
MCC	Material Consumption in Construction
MCS	Monte Carlo Simulation
MEF	Modified Energy Factor
MSW	Municipal Solid Waste
NAA	Neighborhood Accessibility and Amenities
NIS	Negative-Ideal Solution
NZEB	Net-Zero Energy Building
OC	Operational Costs
ODP	Ozone Depletion Potential
PAF	Potentially Affected Fraction of species in an environment
PDF	Probability Density Function
PIS	Positive-Ideal Solution
PL	Performance Level
PLF	Performance Level Function
PMF	Probability Mass Function
POI	Profitability of Investment
PV	Photovoltaic
RE	Renewable Energy use
REP	Renewable and Environmentally preferable Products
RESNET	Residential Energy Services NETwork
RM	Regional (local) Materials
ROI	Return on Investment
RSI	R-value Systeme International
SD	Site Disruption and appropriate strategies
SEER	Seasonal Energy Efficiency Ratio
SI	Severity Index
SP	Smog Potential
SPCs	Sustainability Performance Criteria
SPIs	Sustainability Performance Indicators
SPS	Sustainability Performance Scale
SPSS	Statistical Package for Social Sciences
SS	Site Selection
SSB	Safety and Security of Building
TBL	Triple Bottom Line
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRACI	Tool for the Reduction and Assessment of Chemical other environmental

Impacts	
UAS	User Acceptance and Satisfaction
UBC	University of British Columbia
WE	Water and wastewater Efficiency strategies
WF	Water Factor
WGR	Waste Generation Rate
WHS	Workforce Health and Safety

Acknowledgements

All praises be to the ALLAH Almighty who gave me the strength to materialize this research in the present form. I would like to express my sincere appreciation to my advisor, Dr. Kasun Hewage, who believed in me, trusted in my abilities, encouraged me to grow as a researcher, and strive for the best. Dr. Hewage has been an inspiration as long as I have known him and I am deeply grateful that I had the chance to work under his supervision for my PhD at The University of British Columbia (UBC). Dr. Hewage is an outstanding mentor and a passionate researcher and I am extremely thankful for his wisdom, patience, kindness, passion for success, and research vision. You have been an incredible mentor for me during my challenging research journey.

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Lovingly dedicated to

My parents

&

My beloved wife, Nassiba

Chapter 1 Introduction

This chapter briefly discusses the problem statement, research motivation, research gap and questions, research goal and the associated specific objectives. In addition, an overview of the thesis structure to achieve the research objectives is provided.

1.1 Background and Motivation

Sustainability is defined as a set of processes aimed at delivering efficient built assets in the long-term (Egan 1998). It is adopting a strategic view of enhancing the impacts of human developments on the environment by satisfying the requirements of people today without undermining the ability of next generations to meet their own needs (Brundtland Commission 1987). A rigorous analysis of the evolution of the sustainability concept in the scientific community was conducted by Bettencourt and Kaur (2011). The authors assembled a large body of scientific publications between 1974 and 2010 that contained the words 'sustainability' and/or 'sustainable development' in their abstract, title, or keywords. Overall, they found 20,000 papers, authored by about 37,000 authors found in 174 countries. This is a large amount of publications, which testifies to the extraordinary growth of interest in sustainability assessment over time. These figures alone say a lot about how urgent and global the topic of sustainability is, and how much it has developed.

There is a significant demand for development of new buildings and infrastructure to accommodate the rapidly increasing population of the world (Lim et al. 2015). It is estimated that the construction industry contributes to 13% of global economy and employment of over 110 million workers around the world (Ajayi and Oyedele 2018; Economy Watch 2010). However, this industry accounts for significant environmental, economic, and social impacts (Han et al. 2017) by consuming approximately half of the global resources (Achal et al. 2015). The construction industry is the largest consumer of material resources (40- 60% of the total raw material extractions), water, and energy (40% of energy consumption). It also accounts for significant amount of CO_2 emissions to the environment (up to 39% of the total emissions) and largest waste to landfills (Bilal et al. 2016; Edwards 2014; Ahn et al. 2009; Achal et al. 2015; Bribian et al. 2011). Thus, the construction development should be accompanied by careful considerations to reduce its negative burdens on the environment and societies.

Achieving sustainability is one of the most challenging contemporary concerns, which means using natural resources to fulfil current generation needs while not threatening future generations' quality of life. Sustainable construction, in particular, aims at reducing the environmental impact of a building over its entire lifetime, while optimizing its economic viability and the comfort and safety of its occupants. In other words, the built environment including buildings can result in momentous environmental, economic, and social impacts (namely triple bottom line or TBL) as the primary dimensions of sustainable construction (Sev 2009). Therefore, the construction industry can actively contribute to the sustainability agenda by means of sustainable construction (Lim et al. 2015). Consequently, there has been a paradigm shift in the construction industry over the last few years and the sustainable construction is grabbing more attention globally among construction stakeholders such as firms and clients (Valdes-vasquez et al. 2012). Nonetheless, the lack of broad knowledge on sustainability in terms of methodologies and expected long term benefits is still a significant hindering factor of construction of sustainable buildings (Ahn et al. 2013; Cotgrave and Kokkarinen 2011; Chong et al. 2009). One of the most effective solution to achieve the goals of sustainable construction is to intensify sustainability knowledge and expertise within the construction industry (Shelbourn et al. 2006). In addition, the public awareness of the life cycle advantages of sustainability can play an important role towards expansion of sustainable construction.

Three industrial revolutions have already occurred. During the past few years, digital progress has transformed whole industries, ushering in a new technological era now known as the Fourth Industrial Revolution. New technologies can address both consumer needs and companies' sustainability and productivity. New technologies in the construction industry, such as building information modeling (BIM), prefabrication and modularization, and automated and robotic equipment, can significantly affect the entire construction industry. Although this industry still follows its traditional approach, it has been exposed to the process of industrialization and experimenting different methods of construction. As a result, off-site construction came into practice as a potential alternative to conventional on-site (also called traditional, site-built, stick-built) construction which shows signs of revolutionizing the housing market. Off-site construction refers to the process of manufacturing and preassembling building elements, components, or modules prior to their installation on the final project site (Goodier and Gibb 2007). Modular construction, as the primary method of off-site construction, is fast evolving as an effective alternative to conventional (on-site) construction. A modular building comprises a set of modules that are built in an off-site fabrication center, delivered to the construction site, assembled, and placed on a permanent foundation. Each modular building normally has multi-rooms consisting of three-dimensional modules. The modules are built and pre-assembled in factory environments and all the mechanical, electrical, plumbing, and trim work is done (O'Brien et al. 2000). Upon the completion by the manufacturer, these units are shipped to the site for installation on foundations much like a site-built building (Cameron and Di Carlo 2007).

About 85% to 90% of the modular construction work is done off-site and the remaining (10% to 15%), including the foundation and utility hookups, is done on the final building location on site (Kawecki 2010).

It is imperative to comprehensively assess the life cycle sustainability performance of different construction methods because of the importance of sustainable construction. This can be accomplished by analyzing and comparing the sustainability performance of buildings constructed using on-site and off-site construction methods. Therefore, the motivation behind the proposed research is to compare and contrast the comparative sustainability performance of residential modular vs. conventional buildings over their life cycle.

1.2 Research Gap

During the past few years, new methods of construction have been gaining attention as effective alternatives to conventional methods in the pursuit of sustainable construction. In this regard, the topic of off-site construction has been of major interest due to push towards minimizing construction and demolition waste and increasing sustainability in construction industry (Yeheyis et al. 2013). Modular construction, as the primary method of off-site construction, is a rapidly growing technique that can be applied to different types of buildings, such as residential single and multi-family buildings, educational centers and student housing, hospitals, offices, hotels, and so forth. It has been reported in the published literature that modular construction offers various benefits over the traditional construction (Arif and Egbu 2010; Kamali and Hewage 2016). However, despite the claimed advantages, the application of modular construction is still limited in practice. For example, buildings in the developing countries are rarely constructed using off-site and modular construction methods (Mao et al. 2015). The use of modular construction in the building sector of the developed countries is more than that of the developing countries; however, it is not still extensive (Quale et al. 2012).

A key reason for the limited application of modular construction is the clients' reluctance to fully accept innovative construction techniques' added benefits to a project (Pasquire and Gibb 2002). According to the literature, the public's negative perception of the off-site construction methods is one of the significant challenges to modular construction. This is because of the difficulty of ascertaining the advantages that modular construction provides over the conventional methods. For example, modular and prefabricated homes are usually believed as trailers, mobile homes, or manufactured houses (Boyd et al. 2013; Haas et al. 2000). However, similar to conventional buildings, modular buildings are permanent structures that are built according to codes, which are more restrictive than the codes for temporary and transportable trailers. Not only for the public, but also for many of those involved in the construction industry, the benefits of off-site construction techniques have not been well understood. Therefore, decisions on the selection of off-site construction methods are mostly made according to anecdotal evidence rather than solid analytical evidence (Na 2007; Pasquire and Gibb 2002; Blismas et al. 2006).

Published peer-reviewed literature on the topic of life cycle sustainability performance of modular construction is very limited. Only few studies addressed the environmental performance of modular buildings. No significant published study was found on the other key dimensions of sustainability (i.e., economic and social).

Based on the above noted concerns, the following specific research questions emerged in this research:

i. How can the claimed benefits of modular buildings be quantitatively investigated?

ii. What are the most significant sustainability criteria when comparing modular and conventional buildings?

iii. How can the life cycle performance of residential modular buildings be assessed using objective indices?

iv. How can the underperforming areas of modular buildings be managed to improve their performance?

v. How can the most sustainable building option be prioritized between the modular and conventional options?

It is envisaged that a comprehensive sustainability performance assessment of residential modular buildings over the entire life cycle can fill the research gap by answering the above stated questions.

1.3 Goal and Objectives

The primary goal of this research is to improve sustainable construction by developing a methodical and practically applicable life cycle based sustainability performance assessment framework for single-family modular buildings in North America. In this research, the environmental and economic dimensions of sustainability are analyzed and the social dimension is left for future research. In other words, this research addresses the enviro-economic assessment of residential modular buildings. The following are the specific objectives of this research:

1- Identify and prioritize appropriate sustainability performance criteria (SPCs) for modular buildings;

2- Develop sustainability indices for benchmarking the performance of modular buildings.

3- Establish suitable sustainability performance assessment scales.

4- Develop a holistic decision support framework for sustainability assessment of residential modular buildings.

5- Evaluate the performance evaluation of modular buildings in the Okanagan, British Columbia, Canada.

1.4 Meta Language

There are diverse models, techniques and methods that have been used in this research each involved specific and technical vocabularies. However, certain principles and terminologies can have broad meanings. Therefore, it is important to properly understand the terminology developed for this research in order to appreciate the integrated concept of sustainability performance assessment for residential modular buildings. For the purpose of consistent understanding, the specific terms used in this thesis are specifically defined as follows:

- *Conventional/traditional construction*: These terms have been interchangeably used and referred to on-site construction method (also called site-built and stick-built).

- *Conventional/traditional buildings*: These terms have been interchangeably used and referred to buildings constructed by on-site construction method.

- *Technique*, *method*, and *methodology*: These terms have been interchangeably used for any calculation methods such as multi-criteria decision analysis (MCDA) methods. In addition, the 'technique' and 'method' represented the on-site and off-site construction methods such as modular construction method.

- *Framework*: A framework is, or contains, a (not completely detailed) structure or system for the realization of a defined result/goal. In this research, framework referred to holistic methods (e.g., framework for holistic sustainability assessment, framework for identification of sustainability criteria).

- *Decision support framework (DSF)*: This term represented the integrated sustainability performance assessment framework developed in this research. It is a system of methods, modules, calculation tools, and different frameworks to aid decision making.

- *Benchmarking*: This term referred to the performance comparisons of a given building with the least/most desirable performances of other buildings.

1.5 Thesis Structure

The thesis contains eight chapters to achieve the aforementioned research objectives. Figure 1.1 illustrates the organization of the thesis chapters and their interconnections with the research objectives. Chapter 1 describes the problem statement, research motivation, research gap and questions, research goal and objectives, and thesis structure.

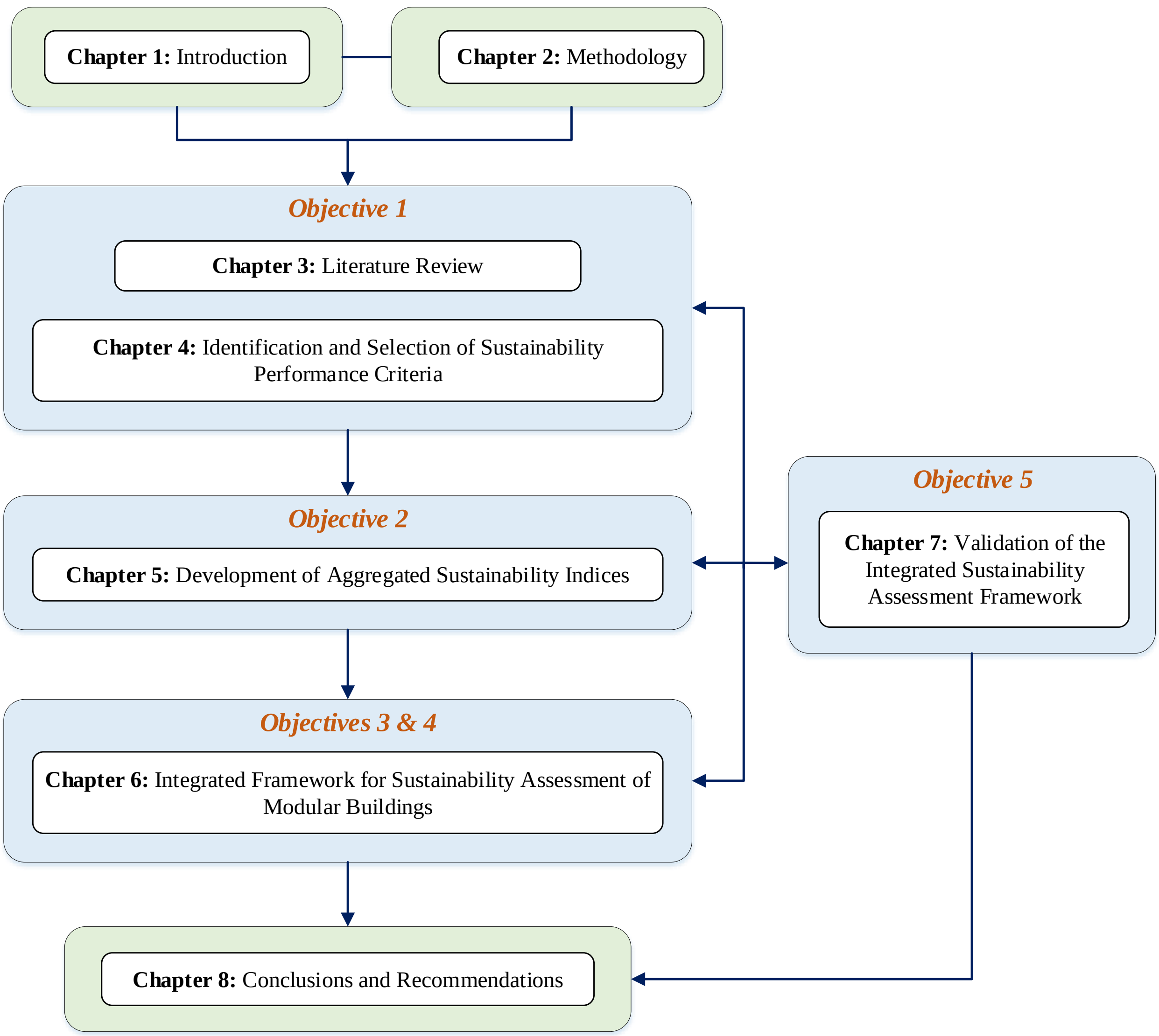

Figure 1.1 Thesis chapters and associated objectives

Chapter 2 briefly overviews the methodology adopted in this research. Then, Chapter 3 presents a comprehensive literature review on the sustainability assessment methods, the advantages and challenges of modular buildings, and the existing studies performed on life cycle sustainability assessment (LCSA) of these buildings. Chapter 4 compiles and ranks the primary potential sustainability performance criteria (SPCs) for the performance assessment of residential modular buildings. Next chapter, Chapter 5, focuses on quantification of the selected SPCs by establishing a method to develop sustainability indices at different levels (i.e., SPC level, sustainability dimension level, and overall sustainability level). Chapter 6 establishes suitable sustainability performance scales for benchmarking the performance of a modular building using the sustainability indices. In addition, this chapter incorporates the research outcomes into an integrated sustainability assessment framework (i.e., decision support framework, DSF). Then, Chapter 7 validates the developed integrated sustainability assessment framework using case study analyses of modular buildings in the Okanagan, British Columbia, Canada. Finally, Chapter 8 discusses the research conclusions, contributions, limitations, and provides recommendations for future research.

Chapter 2 Research Methodology

A part of this chapter has been published in *Proceedings of the Canadian Society for Civil Engineering International Construction Specialty Conference (6th CSCE/CRC)* entitled "Sustainability performance assessment: A life cycle based framework for modular buildings" (Kamali and Hewage 2017a).

An overview of the research methodology is illustrated in Figure 2.1. To achieve the research objectives, six methodological phases have been completed. The detailed methodologies have been provided in the following individual chapters.

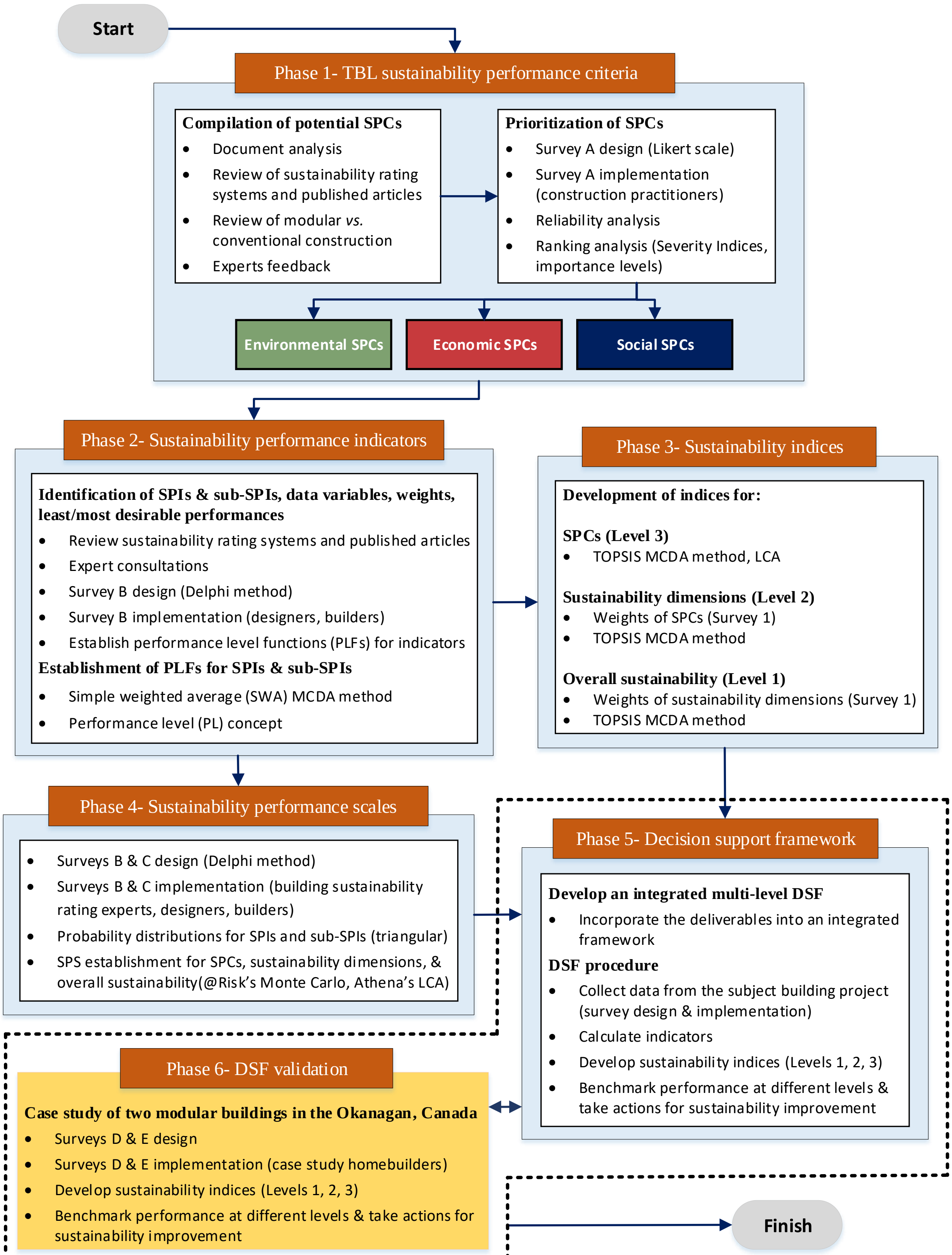

Figure 2.1 Research methodology followed in the research phases

2.1 Phase 1

The first phase of this research identified, ranked, and selected suitable sustainability performance criteria (SPCs) for residential modular buildings (Objective 1). There are different performance areas that can significantly contribute to the life cycle sustainability of buildings, such as energy, material, cost, and so forth. To efficiently evaluate the sustainability of a building, each area can be broken down into a number of assessment criteria, namely sustainability performance criteria (SPCs) in this research. Although, a breadth of literature is available on performance areas for conventional buildings, there is still a gap exists for identification and prioritization of suitable SPCs for performance assessment of residential modular buildings. In this regard, first, the literature regarding rating systems and other published studies were reviewed and experts were consulted to compile the primary potential SPCs and group them into the TBL sustainability categories (i.e., environmental, economic, and social). These SPCs were then incorporated into a questionnaire survey (Survey A) using the LiveCycle Designer tool. Survey A was designed and conducted to capture the construction industry feedback on 'applicability' (relevance) of the compiled SPC categories for sustainability assessment of residential modular buildings. The survey sample population was mainly construction experts in North America who had experience in construction processes and had diverse professional backgrounds. Each SPC was rated using a five-point Likert scale. The data collected through Survey A was analyzed using two standard analyses of reliability analysis and ranking analysis and the Severity Index (SI) scores of the SPCs were calculated with the help of SPSS statistical software. Subsequently, all the SPCs were assigned importance levels ranging from 'Extremely Low' to 'Extremely High' (according to their SI scores) and ranked within each sustainability category.

In this research, all the environmental and economic SPCs with the importance level of 'Medium' and above were selected for evaluation of modular buildings. As mentioned before, the social sustainability assessment of modular buildings is beyond the scope of this research.

Phase 1 was completed in Chapter 4. In section 4.2 of that chapter, the above methodology has been explained in detail.

2.2 Phase 2

Phases 2 and 3 collectively addressed Objective 2 of the research. Phase 2 sought suitable measurable sustainability performance indicators (SPIs) under each selected SPC by which it can be calculated. It is not unlikely that an SPI itself consists of a number of sub-SPIs. Similar to what was done for compiling SPCs, a literature review and also expert interviews were carried out to determine suitable SPIs (and sub-SPIs), their data variables, their least/most desirable performance values, and also their relative importance weights. In the cases of some SPCs and the associated SPIs, the information regarding the least/most desirable performance values was not available in the literature or, even if available, should be determined locally due to sensitivity of the information to the region in which buildings are constructed (i.e., locality sensitive criteria). To collect the required information of such cases, a questionnaire survey (Survey B) was designed and implemented based on the Delphi method along with expert interviews.

The approach followed in this research involved choosing simple and easy-to-use measurement methods for SPIs (and sub-SPIs) by which each indicator can be calculated by having the minimum amount of data including quantitative and qualitative. By using the determined data variables of each indicator (SPI, sub-SPI) and their ranges, the measurement method of the indicator was formulated. To this end, a performance level function (PLF) was established for each SPI and sub-SPI by which its performance can be calculated using the collected data, and presented in a normalized form based on a performance level (PL) between 0 and 100. The PLs of 0 and 100 represent the least and most desirable performances of the subject indicator, respectively, which were already determined through the aforementioned literature review and expert consultations/survey.

Phase 2 was completed in Chapter 5. The detailed methodology of this phase has been provided in the methodology section of that chapter (i.e., section 5.2).

2.3 Phase 3

The next step of the research was to develop aggregated sustainability indices for benchmarking the performance of modular buildings. Using a bottom-up approach, this research developed sustainability indices at the following levels:

- Level 3: SPCs;
- Level 2: Environmental performance and economic performance; and
- Level 1: Overall sustainability performance.

At Level 3, a sustainability index was developed for each SPC through an aggregation process by combining the calculated SPIs (PL values) and their relative importance weights. The required weights of SPIs were determined through the literature review and expert opinions. For the aggregation process, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) multi-criteria decision analysis (MCDA) method was used, which is based on the relative closeness to the best performance and relative remoteness from the worst performance.

Similarly, at Level 2, a sustainability index for the environmental performance (*ENVRi*) and a sustainability index for the economic performance (*ECONi*) were developed by aggregating the developed sustainability indices of all SPCs associated with each sustainability dimension and their weights. The above stated Severity Index scores of the SPCs were used to calculate their weights.

In the same way, at Level 1, the overall sustainability index (*OVERALLi*) was derived by aggregating the environmental and economic sustainability indices developed above and the weights of these sustainability dimensions. These weights were determined based on the construction practitioners' feedback in the same Survey A described above.

In addition to the previous phase, Phase 3 was also completed in Chapter 5. The detailed methodology of this phase has been described in section 5.2.

2.4 Phase 4

In order to evaluate the performance of a modular building, the developed sustainability indices should be compared with the industry's performance benchmarks of similar conventional buildings. In this phase, suitable sustainability performance scales (SPSs) were established for SPCs, sustainability dimensions, and overall sustainability (Objective 3). The following data sources can be utilized to collect the required data and establish such SPSs:

- A database that contains the historical performance of conventional buildings with respect to each SPCs and the associated SPIs and sub-SPIs.
- Opinions of experienced experts on the historical performance of conventional buildings with respect to each SPCs and the associated SPIs and sub-SPIs.

Because the former data source was not available in the literature for many of the criteria and indicators, an attempt was made to create the latter data source. Subsequently, two surveys including Survey B (the same survey that explained under Phase 2 with added questions) and Survey C were designed and implemented based on the Delphi method to capture the construction experts' feedback on the historical performance of buildings with respect to the sub-SPIs and SPIs. The collected data was used to construct the probability distributions of the sub-SPIs and SPIs. Subsequently, these distributions were used to generate the probability distributions of the corresponding SPCs using the Monte Carlo simulation (MCS) method. The @Risk software was employed to perform the MCS analyses. Similarly, the generated probability distributions of the SPCs were used as input of new analyses to generate the probability distributions of the sustainability dimensions. This method continued to develop the probability distribution of the overall sustainability.

Eventually, using the results of distributions associated with each Level, the corresponding SPSs were established by assigning four performance categories including Low, Fair, Good, and Excellent to index range between 0 and 100. Therefore, the performance of a given modular building can be benchmarked by comparing the developed index and the corresponding SPS. It should be stressed that, it was not possible to establish a SPS for the 'Greenhouse gas emissions (GE)' SPC. However, in this research, the review benchmarking method was used to compare the GE performance of the modular and conventional buildings based on the results of the life cycle assessment (LCA) method. The required data for LCA of the case study modular and conventional buildings was collected separately using a separate survey (Survey D) and then the Athena software was used for the LCA analyses.

Phase 4 was completed in Chapter 6 and the above methodology has been explained in details under section 6.2.

2.5 Phase 5

In response to Objective 4, in this phase, all the research outcomes were incorporated into an integrated sustainability assessment framework as a multi-level decision support framework (DSF) that can be used to comprehensively assess the sustainability of residential modular buildings. The developed DSF integrated the individual frameworks used to fulfill Objectives 1 to 3 of the research. Despite the bottom-up approach used when developing the sustainability indices and sustainability performance scales (SPSs) above, the sustainability performance assessment process follows a top-bottom approach. The assessment starts at Level 1 (i.e., overall sustainability performance of the subject building) and can continue up to Level 3 (i.e., performance of the subject building with respect to each SPC) depending on the purpose and scope of assessment determined by the decision maker (DM).

Similar to Phase 4, Phase 5 was also completed in Chapter 6. Thus, the detailed methodology of Phase 5 can be found in section 6.2.

2.6 Phase 6

In this phase, the developed DSF was validated by two case study modular buildings in the Okanagan, British Columbia, Canada (Objective 5). To collect the data required for calculating the sub-SPIs and SPIs, another survey (Survey E) was designed and conducted. Four modular homebuilders in the Okanagan were contacted and requested for participation in Survey E. Two of them participated and completed the survey. In some cases, the participating homebuilders were provided with more details or clarifications on the requested data through a number of in person meetings or phone calls. The collected data was used in the established PLFs to calculate the PLs of sub-SPIs and SPIs. Subsequently, for each modular building, the aggregated sustainability indices were developed using the TOPSIS MCDA method. As explained above, these indices were then used for performance benchmarking of the two modular buildings at different levels by comparing them with the corresponding SPSs. Consequently, the underperforming areas were explored and given high priorities for improvement actions.

As stated earlier, to benchmark the performance of modular buildings with respect to the GE SPC, LCA analyses needed to be performed. In this regard, Survey D was designed and conducted to collect the required data. In addition to the two participating modular homebuilders above, one conventional homebuilder in the Okanagan also participated. Subsequently, LCA was performed for the three buildings (two modular and one conventional) and their global warming potential (GWP) values as the main environmental impact incurred by greenhouse gas emissions (i.e., GE SPC) were calculated and benchmarked. In addition to GWP comparisons, seven additional environmental impact measures were calculated including smog potential, ozone depletion potential, and so forth. These calculated measures along with their relative importance weights were aggregated using an AHP-based framework (Analytic Hierarchy Process) to develop a set of environmental impact indices for each building. Comparisons of these indices comparatively revealed the environmental impacts of the buildings at their material production phase, the construction phase, and the overall cradle-to-gate (before occupancy).

Chapter 3 Literature Review

A part of this chapter has been published in *Renewable & Sustainable Energy Reviews* entitled "Life cycle performance of modular buildings: A critical review" (Kamali and Hewage 2016).

This chapter contains a state-of-the-art literature review of sustainability assessment methods for buildings, benefits and challenges of modular construction, and studies conducted for life cycle sustainability assessment of modular buildings.

3.1 Background

Conventionally, a building is constructed on the construction site after the design phase and a contractor is hired to build it. This process is commonly known as "on-site", "site-built", "stick-built", "conventional", or "traditional" construction. Since the late 19th century, this method of construction has been the accepted construction method and nowadays it accounts for a significant portion of the housing industry (Zenga and Javor 2008). However, in the past few decades, the construction industry has been exposed to the process of industrialization; therefore, it has experienced different methods of construction. As a result, off-site construction came into practice as an alternative to the on-site method.

Off-site construction refers to the process of manufacturing and preassembling of building elements, components, or modules prior to their installation on the final project site (Goodier and Gibb 2007). Based on the degree of work off the project site (i.e., building's final location), off-site construction is categorized into the following levels (Gibb and Pendlebury 2006):

- Component subassembly: Small-scale elements are assembled in factory environments (e.g., windows);
- Non-volumetric preassembly: Items are assembled in factory environments to form non-volumetric units before installation on project sites (e.g., cladding panels);
- Volumetric preassembly: Similar to the previous level, items are assembled in factory environments but they form volumetric units (i.e., units enclose usable space) before installation on project sites. Units are usually fully finished internally (e.g., toilet pods); and
- Complete (modular) construction: Items are assembled in factory environments to form fully finished modules. Whole buildings are formed by a number of modules.

Modular buildings are a set of modules that are built in an off-site fabrication center, delivered to the construction site, assembled, and placed on the permanent foundation. A modular building normally has multi-rooms consisting of three-dimensional modules. The modules are built and preassembled in factory environments and all the mechanical, electrical, plumbing, and trim work is done (O'Brien et al. 2000). Upon completion by the manufacturer, these units are shipped to the project site for installation on foundations, much like a site-built project (Kawecki 2010; Cameron and Di Carlo 2007). About 85% to 90% of the modular construction is done off the construction site and the remaining work (10% to 15%), including foundations and utility hookups, is done on site (Kawecki 2010).

Modular construction, as one of the off-site construction methods, is fast evolving and effective alternative to traditional on-site construction. The application of modular construction is found mainly in general building construction, particularly apartment buildings, schools, hotels, student housing, hospitals, offices, single-family developments, correctional facilities, floating projects, and other buildings where units are repetitive (Annan 2008; Moon 2014). The technique is used in North America, Japan, and parts of Europe (Annan 2008; Li et al. 2013).

In general, the adaptation of off-site construction methods in developing countries has not been as fast as that of developed countries (Mao et al. 2015). However, despite the many well-documented benefits that can be derived from the use of these methods of construction, their applications are still limited. For example, the US modular industry accounts for only 2% to 3% of the total new single-family houses and equal or less than 1% of the total new multi-family houses between 2000 and 2014 (USCB 2016). A key reason for clients' reluctance to accept innovated construction techniques is the difficulty of ascertaining the benefits that off-site construction adds to a project (Pasquire and Gibb 2002). For many of those involved in the construction process, the benefits of off-site construction techniques were not well understood (Na 2007). As a result, decisions surrounding off-site construction techniques are largely made based on anecdotal evidence rather than rigorous data (Pasquire and Gibb 2002; Blismas et al. 2006; Blismas and Wakefield 2009).

It is claimed that modular construction provides a wide range of environmental, economic, and social advantages; thus, it can contribute to achieving the goals of sustainability (Ahn and Kim 2014; Nahmens and Ikuma 2012). These advantages, can justify the use of modular construction by the construction industry practitioners as an effective alternative, more than in the past. To gain a deeper understanding of the modular construction's overall sustainability compared to its conventional counterpart, it is imperative to investigate the sustainability performance of modular buildings over the entire life cycle.

This chapter presents a thorough state-of-the-art literature review regarding modular buildings and sustainability. The following sections review the:

- Existing methods for sustainability assessment of buildings (Study 1)
- Key benefits and challenges of modular construction (Study 2)
- Research studies that have been carried out to evaluate the life cycle performance of modular buildings (Study 3)

In each of these independent studies, first, different types of documents such as journal papers, theses, public reports, and so forth, were searched. Then, through a screening process, the abstract/prefaces/conclusion of the found documents were reviewed to narrow them down to the most relevant documents. Finally, the refined documents were carefully reviewed.

In all Studies 1, 2, and 3, combinations of suitable keywords were searched in three different document categories using the following search databases:

- Books and academic theses: UBC library database was used to find an initial list of books and academic theses. The abstracts/prefaces were reviewed and irrelevant documents were discarded.
- Journal and conference articles: “Compendex Engineering Village” database and ASCE library were searched to find journal and conference articles. The search was also limited to articles that were published after the year 2000. These articles were further refined by reviewing their abstracts and conclusions.
- Governmental/institutional reports: The World Wide Web was used to find governmental or institutional reports and publications, which provided information related to the study they were searched for.

Combinations of keywords ‘sustainability assessment’, ‘building’, ‘sustainability performance’, ‘criteria’, ‘indicators’, ‘method’, ‘system’, ‘tool’, ‘standard’, and ‘framework’ were searched in the above search databases to find appropriate documents related to the sustainability assessment methods for buildings (Study 1). In the case of the next study (Study 2), combinations of keywords ‘modular construction’, ‘modular building’, ‘benefit’, ‘challenge’, and ‘advantage’ were searched to compile a list of documents which provided information related to the benefits and challenges of modular construction. Similarly, combinations of keywords ‘modular construction’, ‘modular building’, ‘life cycle performance’, and ‘life cycle assessment’ have been searched to find appropriate documents which reported the studies that have been performed on sustainability assessment of modular buildings (Study 3). Refined count of documents used in the process of literature review is listed in Table 3.1.

Table 3.1 Number of relevant documents used in this research

Reference category	Study 1	Study 2	Study 3
Book, Thesis	2	13	8
Journal/Conference article	14	36	32
Governmental/Institutional report	46	13	4

The final refined documents under each study were reviewed and findings have been reported in the following sections.

3.2 Building Sustainability Assessment Methods

Currently, diverse assessment methods are used to evaluate the sustainability performance of buildings. However, they are different in terms of objectives, scope, and assessment aspects. Some of these methods have been developed for residential buildings, whereas others have been tailored for commercial buildings. The focus area of the methods is also different ranging from only one phase (e.g., the design and construction phase) to the entire life cycle. In addition, a number of sustainability methods evaluate the performance of a building with respect to only one or two criteria associated with one sustainability dimension (e.g., CO_2 emissions that is related to the environmental dimension). The scoring systems are also different. While some sustainability assessment methods assign points to buildings' performance, others evaluate buildings using the calculated values of criteria (e.g., global warming potential).

During this review, the existing sustainability assessment methods were classified, based on their objectives, characteristics, and structures. Consequently, the following categories recommended by some references (IHOBE 2010) have been realized to effectively classify the existing sustainability assessment methods:

- Sustainability assessment systems
- Sustainability assessment standards
- Sustainability assessment tools

Each of these sustainability assessment method categories is discussed below. It should be noted that in cases where a document was presented in a language other than English, supportive English-language documents were searched to explore the content of the original document.

3.2.1 Sustainability Assessment Systems

The sustainability assessment systems (simply called systems) involve methods to evaluate the performance of a building from sustainability point of view, which is usually beyond the minimum performance required in building codes. In many of these systems, there are a number of assessment categories, such as materials or energy, which are used to evaluate the performance of the building with respect to them. Each category comprises a set of relevant performance criteria such as waste management or quality of insulation that collectively address the sustainability performance of the building with regard to the parent category. Similarly, each criterion itself may consist of a number of sub-criteria by which the parent criterion can be quantified. Therefore, the assessment process commences by collecting data of the building to quantify the sub-criteria and criteria. It then continues by scoring the quantified sub-criteria and criteria and determining the building's performance in each assessment category. Subsequently, all the scores are summed up and the overall performance of the whole building is determined by assigning performance indices such as 'Poor', 'Good', 'Excellent', and so forth. Some of the assessment systems take further steps and certify the building based on its performance. In addition to less environmental impacts by a building that assigned 'Good' and higher performance index (or any equivalent terms used in different systems), it is beneficial to both developer/builder and client/user since it provides a positive perception of the building.

The sustainability assessment systems are usually voluntarily and developed by either governmental or non-governmental organizations to be used internationally or exclusively for buildings are constructed in a country depending on the geographical and socio-economic circumstances. Therefore, they are regularly updated to include every changes in the circumstances such as new technologies such as energy efficient strategies, and assessment methodologies such as the life cycle assessment (LCA) method. They have been developed for different types of buildings such as residential, commercial, and even urban development projects (Bernardi et al. 2013; Ferreira et al. 2014). In addition, the systems have been mostly designed to evaluate the performance of new buildings (i.e., new designs); however, in some cases there are systems that address existing buildings (i.e., renovations, extensions).

The sustainability assessment systems are dissimilar in terms of the life cycle phase coverage. The main priority is mostly the use phase followed by the construction phase; therefore, limited attention is paid to the end of life phase. Furthermore, the sustainability assessment systems consider different aspects of the building's sustainability performance related to the TBL sustainability dimensions, i.e., environmental, economic, and social. The primary focus of systems are on the environmental dimension, even though some economic and social criteria are also addressed. The documents reviewed in this section showed that the sustainability assessment systems are the most comprehensive methods among the three method categories.

Rating systems (also called sustainability rating systems and green building rating systems) are among the well-known sustainability assessment systems that were developed to assist with the management of “green” or “environmentally friendly” building projects. During the past few years, rating systems have had a vital role in informing on progress in sustainability practices (Siew et al. 2013). These systems are mostly qualitative tools that deal with sustainability performance of buildings by providing a set of performance criteria and scoring each building project based on those criteria (Castro-Lacouture et al. 2009). Rating systems examine the performance of a “whole building” and allow comparison of different buildings (Fowler and Rauch 2006). However, they suffer from not addressing all the sustainability dimensions and all the life cycle phases. Moreover, the use of these systems in many cases is complicated, time-consuming, and expensive. Table 3.2 lists a number of well-known rating systems.

Table 3.2 Worldwide known examples of sustainability rating systems

Rating System	Country	Launched	Organization(s)
LEED	International	1998	US Green Building Council (USGBC)
Green Globes	US and Canada	2002	Green Building Initiative (GBI), BOMA Canada, ECD Energy and Environment Canada
LBC	International	2006	International Living Future Institute
BREEAM	International	1990	Building Research Establishment (BRE)
SBTool	International	1996	International Initiative for a Sustainable Built Environment (iiSBE)
CASBEE	Japan	2001	Japan Green Build Council (JaGBC)
Green Star	Australia	2003	Green Building Council Australia (GBCA)
ESGB	China	2006	Ministry of Housing and Urban Rural development of the People's Republic of China (MOHURD)
BCA-GM	Singapore	2005	National Environment Agency
HK BEAM	Hong Kong	1996	BEAM Society

3.2.2 Sustainability Assessment Standards

Sustainability assessment standards (simply called standards) are intended to investigate if the performance of buildings is within the pre-defined minimum requirement. The standards are not as comprehensive as the systems. They are not also capable of assessing the performance of the given building with respect to all the life cycle phases, all sustainability dimensions, and even all aspects within a sustainability dimension. They only address limited performances of buildings, mainly energy related aspects. For example, a number of standards evaluate the greenhouse gas (GHG) emissions of buildings in the use phase.

The sustainability assessment standards are not geared towards extensive sustainability assessment or certification. However, they are useful when the performance of the subject building with regard to a specific aspect is concerned. If the results of applying a standard shows high performance of a building with respect to the investigated criterion, it does not necessarily mean that the building is a sustainable product. This is because the performance of the building with respect to all relevant criteria associated with all TBL and also all life cycle phases has not been investigated. However, such a building can be considered a potential candidate to be a sustainable building; therefore, it needs to be tested by a comprehensive method such as a sustainability assessment system.

3.2.3 Sustainability Assessment Tools

Similar to the sustainability assessment standards, the sustainability assessment tools (simply called tools) are not intended to comprehensively assess the sustainability performance of buildings. As the name implies, the tools can be interpreted as means to support the required calculations or measurements indicated in the sustainability assessment systems and standards. In other words, tools provide a methodical framework such as inventory databases, methodologies, among others, to calculate a specific measure or output such as global warming potential using the required data of the given building.

Tools usually do not provide any scoring system, minimum performance requirements, performance levels, or certification types by which the outputs can be interpreted. If the tools are not categorized as an independent sustainability assessment method category, they can be considered as strong support tools for the systems and standards to calculate some of the criteria included in them. For example, LCA is recently becoming a significant criterion and has been included in a number of systems. However, the methodology how to perform an effective LCA study for a building is not included within the same systems. This should be conducted separately using a suitable LCA tool such as Athena or SimaPro and the output is then used as input for the intended system in order to score, compare, or interpret the performance of the subject building with regard to this input. In addition, in many cases, tools are employed in the design phase to assist with the selection of building materials, local service options (energy types, supply systems, equipment), material transportation means, and waste management strategies (Ali and Al Nsairat 2009). Examples of known tool are Athena (for LCA), BEES (for LCA), SimaPro (for LCA), TRNSYS (for energy simulation), eQuest (for energy simulation), One Click LCA (for both LCA and LCC), among others.

The other important point is that the output of a tool (LCA output, embodied energy, and so forth) is sensitive and can significantly be affected from a country to another. Therefore, the databases or data inventories included in a tool should be in accordance with the circumstances of the region it is intended to be used, otherwise the output will be wrong or very inaccurate. There are cases where a huge database is compiled and embedded in a tool by which the region differences are addressed. For example, the Athena LCA software includes the inventory database for different locations in North America.

3.3 Benefits and Challenges of Modular Construction

According to Pasquire and Gibb (2002), advantages and disadvantages of off-site methods in the construction industry should be clearly identifiable and accessible to all construction practitioners, including architects, engineers, contractors, and end users,. Although monetary measures are able to be linked to profitability, they are inadequate to evaluate other benefits such as productivity, safety and wider human factors (Blismas et al. 2006). In fact, the main focus of the traditional performance evaluation frameworks when choosing the construction method is on direct cost. Therefore, other significant advantages that lead to the added value and enhanced sustainability of a building project are generally overlooked (Li et al. 2014).

3.3.1 Benefits of Modular Construction

The significant benefits of modular construction are briefly discussed in this section.

Schedule

One of the most important benefits of modular construction is fast turnaround between "ground breaking" and occupancy. As Figure 3.1 demonstrates, site preparation and building construction activities take place simultaneously in modular construction as opposed to conventional construction (Kawecki 2010; Haas et al. 2000). In addition, the risk of delays due to weather extremes (Na 2007; NAHB 2006; Celine 2009), vandalism, and site theft (Mah 2011; Cartwright 2011) are minimal in modular construction.

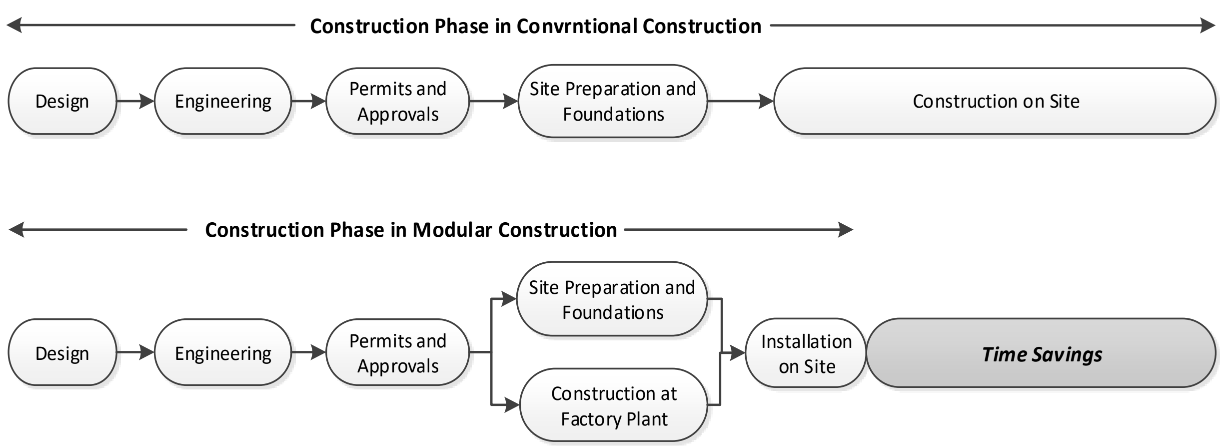

Figure 3.1 Time savings in modular construction. Reproduced from Kamali and Hewage (2016). Used with permission from © Elsevier

Modularization may be a key option for cases where construction deadlines are often inflexible, such as for the education sector, or for projects on active sites (e.g., an extension of a hospital complex constructing a new building) (McGraw-Hill Construction 2011).

Modular construction can save around 40% of construction time compared with traditional construction (Mah 2011; Lawson and Ogden 2010; Smith 2011; MBI 2012a). As an example, Zenga and Javor (2008) revealed that the time needed for completion of a regular modular house was only four months, while a similar conventionally constructed home needed 14 months. In addition, it took 10 months for designing, engineering, and permitting for the modular project, and 21 months for the conventional project. As construction on site is labor-intensive, this time saving can considerably cut down the final cost of a project (Said et al. 2014).

Some literature stated that when the number of stories increases in a modular project (e.g., multi-family vs. single-family buildings), the time savings decreases considerably because the project becomes more complicated and subsequently extra engineering and communication as well as more work in the jobsite are required (Ramaji and Memari 2015). However, the completion time of modular buildings is still less than similar conventional buildings even though the project is a high-rise building (Cartz and Crosby 2007).

Cost

Off-site methods could yield a lower overall project cost due to many related factors (Haas et al. 2000; Lawson et al. 2012; Kozlovská et al. 2014). According to a study by the Construction Industry Institute (CII), quoted in some literature, there was up to 10% savings on the overall cost and up to 25% savings on the on-site labor cost in some modular construction projects (Na 2007; Haas and Fagerlund 2002). Time savings in modular construction can effectively contribute to the economy of modular buildings (i.e., “time is money”). Manufacturing numerous modules simultaneously can save costs because materials can be ordered in bulk and labor and machinery transportation can be reduced (Quale et al. 2012; Chiu 2012). In addition, modular construction decreases the number of laborers on site, which results in less labor congestion leading to higher craft productivity (Na 2007; Haas et al. 2000). Moreover, cost reductions could be achieved by other factors, such as on-site overhead reduction, avoidance of weather extremes, standardization of design, high level of energy efficiency, and higher efficiency in installation (Haas et al. 2000; Cartwright 2011; Haas and Fagerlund 2002).

However, some literature emphasized that the impact of using off-site construction on project costs is not very clear due to a variety of contributing variables (Chiang et al. 2006; Pan et al. 2011; Lawson and Ogden 2008). For example, the lack of access to confidential financial information of projects and the use of modern equipment are among the unknown variables (Na 2007). In addition, according to Schoenborn (2012), if the cost sources of modular construction are not efficiently managed, modular buildings can be more expensive than traditional buildings.

For example, cost savings due to the time savings in modular construction can be offset by the costs associated with the transportation or extra engineering requirements.

On-site safety

The fatality rate in the construction industry has not changed in recent years, even with the overall construction slowdown (Buckley and Ichniowski 2010). Due to the ever-changing nature of on-site work, safety in modular construction is higher since around 85% of the work is done off the project site. Workplace accidents, working at height, congestion, severe weather, dangerous activities, and neighboring construction operations can be reduced by transferring the main construction work to factories with easier and highly repetitive site operations (Na 2007; Li et al. 2013; Haas et al. 2000; McGraw-Hill Construction 2011; Haas and Fagerlund 2002; Chiu 2012; Cartz et al. 2007). According to Lawson et al. (2012), on-site reportable accidents in modular construction can be 80% less than traditional construction (Lawson et al. 2012).

Product quality

Higher quality can be achieved with the use of modular construction due to the controlled manufacturing facilities in which the components and modules are built. Construction under factory conditions, repetitive processes and operations, and automated machinery, can result in a higher level of product quality (Douglas 2006; Haas et al. 2000; Cartz et al. 2007; Rogan et al. 2000; Ambler 2013). In addition, due to smaller tasks in assembly lines, workers become skilled relatively fast (work specialization). In fact, the learning curve is simple, causing less product damage or defects. Moreover, as the modules should have enough strength and load bearing standards when transported by trucks, high quality materials which are durable, lightweight, and resistant to weather are required. Furthermore, reduced material exposure to harsh weather on site can lead to better finished building quality (O'Brien et al. 2000; Cameron, and Di Carlo 2007; Celine 2009; Cartwright 2011; Haas and Fagerlund 2002; Chiu 2012).

Workmanship and productivity

Modular construction and prefabrication require less skilled workmanship on site as the work is less complicated (Blismas et al. 2006; Rogan et al. 2000; Gibb and Isack 2003). In addition, productivity is higher in modular projects due to highly organized operations and possibility of better supervision, reduced time interval between different trades, and workforce stability in modular industry (Celine 2009). Moreover, in manufacturing environments, many parallel activities and operations can continue without any interruption, which can result in higher productivity (Haas et al. 2000; Lu 2009).

Environmental performance

Modular construction have been claimed to offer several environmental benefits. Less waste is one of the most important benefits due to more precise purchasing, planning, and cutting of materials, and also appropriate recycling opportunities (Na 2007; Cameron and Di Carlo 2007; Celine 2009; Lawson et al. 2012; MBI 2012b). According to a report by McGraw-Hill Construction (2011), 76% of the research respondents believed that modular construction can reduce the construction waste. This is because in a modular factory environment it is easier to control, reuse, recycle, and dispose of generated waste (Zenga and Javor 2008; Kawecki 2010; Cartz et al. 2007). In addition, at the end of the modular buildings' life cycle, modules can be disassembled, relocated, or refurbished to be used in other projects instead of disposal (Li and Li 2013). Although less waste is generated, to ensure the required structural strength of modular buildings about 10% to 15% more materials are consumed (Cameron and Di Carlo 2007).

Furthermore, while the traditional methods disturb the project site and surrounding area through on-site construction time, noise, dust, congestion, and waste, modular construction performs better by providing minimal project site disturbance (Na 2007; Celine 2009; Kozlovská et al. 2014; DiGiovanni et al. 2012; Jeng et al. 2011).

On-site reduction of GHG emissions is another benefit of modular systems (Mah 2011; Amiri et al. 2013; Lu and Korman 2010). Reduced construction time leads to less energy consumption, fewer workers' trips, fewer trips by suppliers and subcontractors to the construction sites (due to material delivery in bulk to the factory plants) (Cameron and Di Carlo 2007).

3.3.2 Challenges of Modular Construction

The main challenges of modular construction are briefly described in this section.

Project planning

A significant challenge of prefabrication, preassembly, and modularization is the need for intensive pre-project planning and engineering. Modular design is significantly different from conventional design. In addition to the complexity of modules' design itself, further considerations are needed when incorporating different components within a module, and then when modules are lifted and transported to the project site, placed on the foundation, and joined to form the final building (O'Connor et al. 2016). All these must be considered carefully before the start of component manufacturing and assembly. Complex modules need more engineering design because of the subsequent complexity of interfaces. A clear scope is needed in advance as it is hard to make any changes later during the construction phase (Celine 2009; Haas and

Fagerlund 2002; Lu 2009; Jaillon and Poon 2010).

Transportation restraints

Transportation logistics has a vital role in feasibility of modular systems. Before taking any design step, the modular project team should investigate the limitations of module transportation in the area (O'Connor et al. 2016; Jameson 2007). In addition to studying the general transportation regulations, special traffic control allowance requirements (e.g., staging areas) for heavily populated areas should be checked (NMHC 2016). Generally, it is not possible to transport manufactured houses or completed modules to distant locations because it is costly and requires complex arrangements (Lu 2009; Boyd et al. 2013; Martinez and Jardon 2008; Velamati 2012; Naqvi et al. 2014). Usually modular manufactures have a maximum limit of distance for transportation (Cameron and Di Carlo 2007). The modules' dimensional constraint is another transportation barrier, which can be dictated by the transportation regulations of each country (Mah 2011). The transportation method and route can restrict size, weight, and dimensions of modules (Haas and Fagerlund 2002; Wei et al. 2014). In addition, time delays may be caused by the need for permits for oversized components, or customs delays at borders when transporting internationally (Velamati 2012; Cameron and Di Carlo 2007).

Negative perceptions

Much literature noted the public's negative perception of off-site construction methods. This is a significant factor that hinders the fast development of off-site construction techniques all around the world. As an example, modular and prefabricated homes are usually believed to be or similar to mobile homes (manufactured houses) in the US; however, they are completely different (O'Brien et al. 2000; Haas et al. 2000; Boyd et al. 2013; Rahman 2013; Blismas et al. 2007; BRE 2001). The end users' (clients') lack of awareness on the benefits and different options offered by off-site construction techniques can influence the market demand, and subsequently, the development of these techniques (Mao et al. 2015).

High initial cost and site constraints

A considerable amount of initial capital is needed to set up appropriate machinery to run a modular manufacturing plant (Rahman 2013; Chiang et al. 2006; Celine 2009; Lawson et al. 2012). In addition, local economy is a determining factor to initiate modular construction services in an area. In those areas, where the labor is cheap, new methods of construction may not be possible. Likewise, the lack of availability of knowledgeable and experienced experts, such as engineers and designers who have enough experience for modular systems is a limitation

(Jaillon and Poon 2010; Haas and Fagerlund 2002; Celine 2009). For example, for Chinese developers, finding off-site construction consultants, suppliers, and contractors, is a major difficulty (Mao et al. 2015).

Coordination and communication

There is a need for an increased, more detailed, and more effective coordination in all stages of a modular building project, including pre-project planning, procurement, supply chain scheduling, installation and construction, and delivery. Frequent communication among all stakeholders (owners, engineers, designers, suppliers, and contractors) is required to provide access to the necessary information such as decisions, designs, transportation requirements, and schedules (Na 2007; Haas and Fagerlund 2002; Rahman 2013; O'Connor et al. 2016).

Table 3.3 summarizes the key benefits and challenges of modular construction discussed above.

Table 3.3 Summary of the advantages and disadvantages of modular construction

	Parameters	Description
Advantages	Time	- simultaneous construction work and site preparation - no work disruption due to weather extremes - less vandalism and site theft due to a shorter schedule
	Cost	- labor transportation reduction - machinery transportation reduction - ordering bulk materials and receiving volume discounts - saving due to on-site labor reduction - less site overhead and congestion - reduced interest charges due to fast construction - avoidance of costly delays due to weather or site severe conditions - distribution of overheads, admins, and technician costs over quantity production
	On-site safety	- reduction in elevated work and dangerous activities - reduction in on-site workforce congestion - less workforce exposure to neighboring construction operations - less workforce exposure to severe weather - less working time on-site
	Product quality	- controlled manufacturing facilities - highly engineered fabrication - repetitive processes and operations - automated machinery - specialized skilled workforce - using high quality materials to withstand transportation - less material exposure to harsh weather on-site

	Parameters	Description
	Workmanship and productivity	- less skilled workforce requirement - highly organized operations - better supervision - less time intervals - workforce stability
	Environmental Performance	- waste generation reduction - potential for waste management - less disturbance on-site such as noise and dust - efficient land resources use - reduction in GHG emissions
Disadvantages	Project planning	- need for more pre-project planning - extra engineering effort - hard to make changes later
	Transportation Restraints	- modules' dimensional constraints - hard to transport modules far away - time delays due to late transit permits for oversized components - customs delays in borders when transporting internationally
	Negative perception	- negative perception of new construction methods
	Site constraints	- availability of cheap labor in the area - availability of knowledgeable experts such as engineers and designers in the area
	Coordination and communication	- need for an increased and more detailed coordination in all stages of a project - more communication among all stakeholders
	Initial cost	- need for large initial investment to run modular services

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3.4 Life Cycle Performance of Modular Buildings

As stated earlier, the literature mentioned various benefits offered by modular construction. However, suitable studies that can prove these benefits using real data and analyses are limited. This section presents the current studies on the life cycle performance of modular construction.

3.4.1 Life Cycle Phases of Buildings

In general, the life cycle of conventional buildings consists of four main phases; the production phase, the design and construction phase, the use phase (also called occupancy or operation phase), and finally, the end of life phase. Similarly, in case of modular buildings, there are four phases. However, as shown in Figure 3.2, the tasks in the design and construction phase are different from conventional buildings and comprises building design, module fabrication, transportation of modules to the project site, and assembly on the project site. Materials and energy are consumed in all activities under the life cycle phase of a building such as raw material extracting and processing, product and component manufacturing, transportation of products and components, and energy used for heating, cooling, and lighting. While there are some identical tasks in the life cycle of conventional and modular buildings, there are also many differences, which can be opportunities for reducing the consumption of materials and energy.

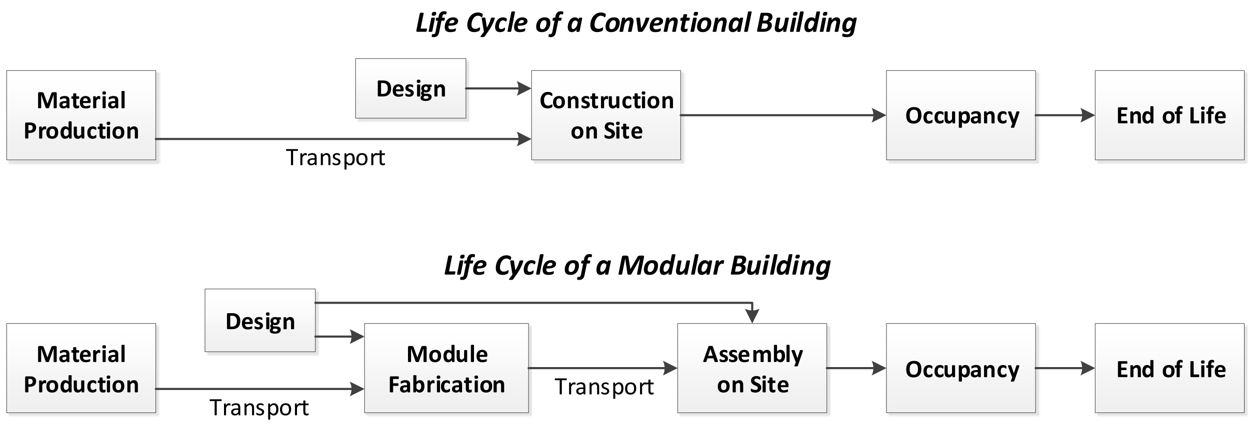

Figure 3.2 Life cycle of modular buildings versus conventional buildings. Adapted from Kamali and Hewage (2017). Used with permission from © Elsevier

It is evident that among the life cycle phases of a building, the use phase has a substantial contribution to environmental impacts (Quale et al. 2012; Scheuer et al. 2003; Sartori and Hestnes 2007). Depending on the design and type of a building, energy consumption in the use phase accounts for over 70% of the total life cycle energy consumption (Ortiz et al. 2009; Keoleian et al. 2000; ODEQ 2010; Scheuer et al. 2003; Monahan and Powell 2011).

Due to more efficient technologies, including design strategies and materials, and environmentally friendly energy resources (e.g., wind and solar resources), buildings are becoming more energy efficient over their occupancy phase. Consequently, other life cycle phases have been growing in importance. According to Gustavsson and Joelsson (2010), the first two phases (i.e., the production phase and the design and construction phase) in an optimally energy efficient building are responsible for around 60% of the total energy used during the life cycle. In addition, for such a building, the embodied energy, and the equivalent embodied carbon, become very important because more energy is required to build high-level insulation systems, additional technologies are incorporated into practice, and heavier mass materials are used. It was suggested that the proportion of the embodied energy could be anywhere from 9% up to 46% for low energy buildings (Monahan and Powell 2011; Thormark 2002).

3.4.2 Life Cycle Performance Studies of Modular Buildings

The literature shows that all the life cycle performance studies for modular buildings have been performed in recent years as listed in Table 3.4. These studies have been limited to the environmental life cycle performance analyses rather than all TBL sustainability dimensions.

Table 3.4 Environmental LCAs associated with modular buildings

Study	Case Studies	Building Type	Location	Principal Structure	Floor Area (m^2)	Lifespan (year)	Investigated Indicator(s)	Assessed Life Cycle Phase(s)	Software or Method
Kim (2008)	modular and conventional	single-family one-story residential	US	wood	135	50	embodied energy, operational energy, CO_2 emissions, waste generation	material acquisition, module fabrication, site assembly, use	SimaPro, BEES, eQuest
Al-Hussein et al. (2009)	modular and conventional	multi-family four-story residential	Canada	wood	2500	NA	CO_2 emissions	module fabrication, site assembly	NA
Kawecki (2010)	modular	Residential	US	wood	NA	NA	CO_2 emissions	module fabrication, site assembly	NA
Monahan and Powell (2011)	modular and conventional	single-family two-story residential	UK	wood (modular), masonry (conventional)	91	NA	embodied energy, CO_2 emissions	material acquisition, module fabrication, site assembly	SimaPro
Aye et al. (2012)	modular and conventional buildings	multi-family eight-story residential	Australia	wood (modular), steel (modular), concrete (conventional)	3943	50	embodied energy, operational energy, CO_2 emissions, end of life waste reuse	full life cycle	SimaPro, TRNSYS
Quale et al. (2012)	modular and conventional	single-family two-story residential	US	wood	186	NA	embodied energy, CO_2 emissions, other environmental impacts	material acquisition, module fabrication, site assembly, use	SimaPro, BEES
Faludi et al. (2012)	modular	one-story commercial (community center)	US	steel	465	50	embodied energy, operational energy, CO_2 emissions, other environmentalimpacts	full life cycle	SimaPro, EnergyPlus, eQuest, EcoIndicator
Paya-Marin et al. (2013)	modular	one-story educational (school)	Ireland (UK)	wood	120	50	embodied energy, operational energy, CO_2 emissions	material acquisition, module fabrication, site assembly, use	IES-VE, Hammond

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Each study had its own approach, scope, and case studies. Some studies compared the environmental performance of modular versus conventional buildings, while others solely focused on comparing different modular buildings. Type of buildings (residential, commercial), their principal structure (wood, steel, masonry), and their size were also different between the studies. Similarly, the studies covered different life cycle phases (ranging from only one phase to full life cycle) and different indicators, and used different methods to perform the analyses. The following section presents the life cycle performance studies associated with modular construction.

- *Kim (2008)*

Kim (2008) performed an LCA on a one-story single-family modular house and a traditional stick-built house in Michigan, US, to investigate the environmental impacts due to different construction techniques over the lifetime of 50 years. The functional unit was considered the usable area (135 m^2). The modular home was modeled based on real data provided by the modular manufacturer. Since it is difficult to find a conventional home with an identical size and comparable conditions, the industry's average data for the same volume and floor area was used to analyze the conventional home. Kim used a life cycle approach to compare the total energy consumption (including embodied and operational energies), resource use, GHG emissions, and waste generation between the two case study buildings. For the modular home, material acquisition, module fabrication, site assembly, and occupancy, were taken into account. Similarly, for the conventional home, the material acquisition, construction, and occupancy phases were included in the assessment process. For both buildings, the end of life phase, as well as maintenance/renovation related tasks were considered to be outside of the research scope. As mentioned earlier, the design, module fabrication, and site assembly in modular construction are comparable to the design and construction phase in conventional construction. SimaPro and BEES databases were used for the LCA of material and energy consumption before the use phase and eQuest was used to simulate the energy consumption during the use phase.

Kim's study confirmed that the use phase is the dominant phase in terms of energy consumption and accounts for 94.8% and 93.2% of the total life cycle energy for modular and conventional buildings, respectively. However, the energy consumption of the modular home was 4.6% less compared to its conventional counterpart. In terms of GHG emissions, the use phase alone emitted more than 95% of the total life cycle emissions in both cases, but still the modular building performed better. The total emissions was presented as the global warming potential in CO_2 equivalent (CO_2-eq)and was shown to be 5% more for the conventional home. Moreover, it was estimated that the on-site construction process generates solid waste up to 2.5 times more than the off-site modular construction process.

- *Al-Hussein et al. (2009)*

In 2009, Al-Hussein et al. focused on the construction phase of modular and conventional buildings and compared their CO_2 equivalent emissions. They analyzed a 42-suite multi-family four-story residential modular building located in Alberta, Canada. All the construction activities needed for this building and a similar conventional building, such as material delivery transportation, workforce trips, equipment usage, and winter heating, were identified and the associated data was collected separately. Subsequently, the CO_2 emissions from each of these activities were quantified. However, the CO_2 quantification, related to the embodied energy of the building materials, was not taken into account. The authors' analyses showed that modular processes led to a 43% reduction in CO_2 emissions compared to on-site processes (Al-Hussein et al. 2009).

- *Kawecki (2010)*

Kawecki (2010) chose a different approach to compute the carbon emissions during production of a modular building. The author quantified the carbon footprint of factory production output, as measured by home, module, and square foot of fabrication, based on observations and data collection during one month in a modular home fabrication company in Pennsylvania, US. All energy consumed for the manufacturing process in the fabrication plant as well as the delivery and installation of the modules on site were taken into account. However, the embodied energy, associated with materials and material delivery to the factory (i.e., production phase), and the construction waste were considered outside of the study scope. Furthermore, only CO_2 emissions were measured and the other greenhouse gases were excluded.

The carbon emissions for a 130 m^2, two-module home was estimated to be 3051 kg of CO_2-eq. The study stated that if the modular factory produces at its full capacity (80 modules per month), for the same home, the CO_2-eq will be decreased from 3051 to 2620 kg. In addition, the researcher compared a three-module residential home with a similar stick-built home and suggested that the modular home produces 30% and, at optimum production rate (80 modules per month), 38% less carbon than the conventional home.

In terms of CO_2 emission sources during the manufacturing period, electricity was found to be the predominant energy source. Records revealed that energy consumption due to electricity is approximately a fixed amount. It means that high production output can lead to cost saving and carbon footprint reduction for each production unit such as a module or a modular home.

- *Monahan and Powell (2011)*

A partial LCA, from cradle-to-gate, was conducted in Monahan and Powell's work (2011). They evaluated the carbon footprints associated with different amounts of embodied energy resulting from different construction approaches. The researchers in this study quantified the embodied energy and the associated embodied carbon for a low energy modular home that was constructed in 2008 in Norfolk, UK. A novel panelized modular timber frame larch cladding system was analyzed in this building. The researchers also modelled two further scenarios to compare the LCA results. The first model was again a panelized modular timber frame but with steel cladding and the second model was a traditional masonry building. All the case study buildings were two-story houses with the same internal floor areas. Each scenario considered the following factors: carbon emissions caused by embodied energies in materials and components, transportation of the materials and modules to the construction site, waste generated on site, transportation of the waste to landfills, and the energy used on-site during construction.

For the first scenario, the total embodied energy was estimated 5.7 GJ/m^2 of floor area which equates to approximately 405 kg CO_2/m^2. It is important to state that 82% of the total embodied carbon was due to materials, of which, minerals alone accounted for 45%. In the case of the modular timber frame brick cladding, the embodied energy and carbon were quantified as 7.7 GJ/m^2 and 535 kg CO_2/m^2, respectively. This means that 35% more embodied energy was consumed and 32% more embodied carbon was produced compared to the first scenario. The conventional case study home was the worst scenario where the embodied energy and embodied carbon increased 35% and 51%, respectively, compared to the low energy modular scenario. Monahan and Powell (2011) argued that this considerable difference in the embodied energy and the consequent carbon emissions was due to the use of materials with relatively high embodied carbon (concrete, brick, and blocks) in the second and third scenarios. For example, in the conventional case study, 67% of the total carbon had embodied in the walls, foundations, and substructure. In addition, the first scenario home had a lighter structure frame; consequently, less sub-structural support was required, which leads to less foundation materials. In terms of transportation of module or materials to the project site, the study suggested that it only accounts for 2% of the total embodied carbon, which was not significant.

- *Aye et al. (2012)*

Aye et al. (2012) quantified and compared the embodied and operational energy of three residential buildings including a prefabricated steel-framed modular building, a prefabricated wood-frame modular building, and a concrete-frame conventional building. The buildings were assumed to be located in Melbourne, Australia. The resulting GHG emissions and the potential areas to manage the generated waste were also investigated. Each building was an eight-story multi-family with the gross floor area of 3943 m^2. The researchers conducted a full LCA study (i.e., cradle-to-grave) by including all life cycle phases of the buildings. The embodied energy was excluded from the study scope because of potential material replacement over the life time. SimaPro database (Australian version) was used for the embodied energy quantifications and TRNSYS was used for energy simulations.

The total embodied energy for the steel-frame modular case study was reported around 50% more than the concrete-frame conventional case, while the total mass of the latter building was much more than the former building (four times). The total embodied energy for the steel-frame modular, wood-frame modular, and concrete-frame conventional case studies was calculated as 14.4, 10.5, and 9.6 GJ/m^2, respectively. According to the authors, this was due to higher energy-intensive steel manufacturing processes compared to concrete. For all the construction techniques, the greatest material volume consumed in external walls (followed by the floor panels), accounting for the total material volume of 39%, 47% and 49% for the concrete-frame conventional, wood-frame modular, and steel-frame modular buildings, respectively. It meant that these assemblies were potential assemblies for waste reduction through the use of more durable materials as well as implementing a better construction waste management strategies such as reuse and recycling.

As known, the total life cycle energy is the combination of embodied and operational energy. The study showed that there is only a minor variance in energy use during the occupancy period among different construction methods. The estimated life cycle energy, in the case of the steel-frame modular building, was 36 GJ/m^2, which was greater than that of the concrete building (30 GJ/m^2). The embodied energy represented at least 32% of the total life cycle energy for the case study buildings, which revealed the importance of suitable strategies to reduce the embodied energy in the design, material use, and end of life stages. Regarding greenhouse emissions, the study indicated that the steel-frame modular building emitted 13% more over the life cycle compared to the conventional building. The percentage of GHG emissions associated with the embodied energy ranged between 21% and 27% of the total emissions for all the case studies. If the embodied emissions due to replacement of potential materials and components over the use phase were taken into account, this percentage became even higher.

According to the researchers, although in their study the conventional building consumed less energy than the two modular buildings; however, new construction methods, such as modular technique, are capable to provide better environmental impacts through using less embodied energy-intensive materials and including reuse strategy in the initial building designs. Therefore, less embodied energy requirements and subsequent GHG emissions can be achievable.

- *Quale et al. (2012)*

The next study regarding environmental LCA of modular building was conducted by Quale et al. in 2012. The researchers focused on the construction phase of modular and traditional buildings and quantified the energy consumption from cradle to end of construction (i.e., cradle-to-gate), and compared the consequent environmental impacts between the two construction methods. The case study buildings included three residential modular buildings and five conventional buildings all were two-story wood-frame homes with the floor area of 186 m^2. The required data such as utility bills, worker transportation, materials and waste information, employee and construction schedules, and so forth, was taken from three residential modular companies based on their completed projects. Finding two versions of a building constructed with two different techniques is impossible. Thus, after compiling the specifications for the modular buildings, conventional homebuilders were asked to provide the data if they were going to build on-site buildings in the same region using the same specifications.

The embodied energy for modular case studies was estimated in different categories including material quantities, material transportation, and labor transportation, along with the energy consumed in the modular factory, when transporting modules, and assembling them on the project site. For the conventional buildings, material quantities, material transportation, and labor transportation were considered along with the energy consumption on-site. SimaPro database was used for LCA analyses. Subsequently, a set of environmental impacts including GHG emissions, non-cancer, carcinogens, acidification, eutrophication, criteria pollutants, eco-toxicity, water, smog, and finally, ozone depletion were estimated for each of the case study buildings.

The results of GHG emissions for the modular and conventional buildings showed that, on average, modular buildings have lower environmental impacts compared to their counterparts. Average GHG emissions for modular buildings was estimated to be nearly 6 tonnes of CO_2-eq less than that of traditional buildings per 186 m^2 home. Furthermore, energy consumption on-site and labor transportation significantly contributed to GHG emissions in conventional construction, which revealed the potential areas to reduce the environmental burdens. In addition to the carbon footprint, other impacts were moderately higher in case of conventional buildings.

- *Faludi et al. (2012)*

Faludi et al. (2012) conducted a life cycle assessment to compare only modular buildings at different levels of energy efficiency technologies in their operation phase. As mentioned earlier, there is a positive trend toward design and construction of new systems of “zero- energy” or low energy buildings. As energy demand in buildings is becoming more efficient over the operation phase, due higher efficiency technologies and more environmentally friendly energy resources, the energy consumption within the production phase and the design and construction phase is becoming more important than it was before. Therefore, designers and architects should take into account all these phases to optimize the energy impacts in the operation phase. This can be achieved through the use of higher efficiency technologies in the occupancy phase and also by choosing efficient materials and other embodied energy resources in the production phase and the design and construction phase.

As stated by the authors, the work aimed to clarify the top design priorities for the design of higher sustainable modular buildings. The case study building was a 465 m^2 commercial modular building (new community center) with a steel frame built in San Francisco, US. Three scenarios for energy consumption systems were defined for this study. (1) average Northern California energy use; (2) “as built” building in which 30% of the energy is supplied by rooftop photovoltaics, and remaining by grid electricity; (3) a net zero energy system (photovoltaics supply 100% of energy). The LCA was performed for each of these scenario buildings by including the whole life cycle from the material production phase to the end of life phase using the SimaPro software. For energy modeling in the use phase, both eQuest and EnergyPlus software were used.

The LCA results showed that energy consumption in the operation phase had the greatest impacts. The next important area for reducing the environmental impacts was construction materials choices. However, once a building is approaching net zero energy (third scenario), material choices and manufacturing become the top priority area, which makes the largest environmental impacts. As seen in this study, 55% of the total GHG emissions was associated with the material embodied energy.

Another important result of this work was that GHG emissions are not necessarily well correlated with other environmental impacts. A good example is the concrete used in foundation, which represented the 3^{rd} highest greenhouse impact but the 7^{th} highest total life cycle impact. In addition, the results of the study demonstrated that any decisions in design stage of a modular project can be rationally prioritized and directed based on the LCA results to reduce the total environmental impacts. For instance, while eliminating the under-floor cooling and heating system is beneficial in terms of reducing the material impact intensively, it can increase the energy consumption within the operation phase.

- *Paya-Marin et al. (2013)*

Similar to the study performed by Faludi et al. (2012), in another work by Paya-Marin et al. (2013), the life cycle performance of two modular schools were assessed to compare their energy and environmental impacts. Two 120 m^2 school buildings with different materials and energy system were investigated. The first one was a typical modular school called "Standard building" built in Northern Ireland, UK. The other one was called "Eco building", which was modeled with different materials, HVAC (Heating, ventilation, and air conditioning) system, lighting system. In addition, a photovoltaic (PV) was modeled to supply a portion of the school's energy.

The results of the LCA stated that the embodied carbon in the case of the standard building was 60% more than that of the Eco building. Likewise, the Eco building emitted 48% less GHG emissions annually. It can also be understood from this study that there is no difference between modular and convention al buildings in terms of the capability to accommodate energy efficient technologies, such as low-emissivity windows, thermal insulation, efficient HVAC systems, and daylighting controls.

3.5 Summary

In this chapter, a state-of-the-art literature review was conducted and presented. In the first part of this chapter, the existing sustainability assessment methods were reviewed. These methods can be classified into three categories of sustainability assessment systems, sustainability assessment standards, and sustainability assessment tools. The sustainability assessment systems involve methods to evaluate the performance of a building from sustainability point of view, which is usually beyond the minimum performance required in building codes. In contrast, sustainability assessment standards are intended to investigate if the performance of buildings is within the pre-defined minimum requirement (e.g., building codes). Similar to sustainability assessment standards, sustainability assessment tools are not intended to comprehensively assess the sustainability performance of buildings. They provide means to support the required calculations or measurements indicated in the sustainability assessment systems and standards. Consequently, the sustainability assessment systems are the most comprehensive methods as they are capable to evaluate the sustainability of a building by choosing suitable sustainability criteria related to different TBL dimensions of sustainability and also different life cycle phases. The (environmental) sustainability rating systems are good examples under this category. However, they suffer from not addressing all the TBL and all the life cycle phases. Moreover, the use of these systems in many cases is complicated, time-consuming, and expensive.

In the second part, the advantages and disadvantages of modular buildings were investigated.

Higher speed of construction, better productivity and workmanship, cost savings, higher safety, higher product control and quality, and less environmental impacts, were found the most noticeable advantages of modular construction. In addition, prefabricated and modular techniques have more potential to reuse a proportion of buildings at the end of the use phase in new projects, which can lead to reduction in waste sent to landfills. However, amongst the challenges faced by modular construction were transportation constraints, more complicated engineering and planning processes, need for more coordination and communication, higher initial investment, and more importantly, people's negative perceptions of new construction methods. A few research projects in the last years focused on the benefits and challenges of using new construction methods such as modular building. Nevertheless, most of the literature stated the positive and negative aspects of modular construction qualitatively, not quantitatively. For example, there have been no clear and sound cost analyses, such as life cycle cost analyses, which prove that modular buildings are preferable when compared with similar traditional buildings (from an economic point of view). More importantly, cost should be defined clearly. Cost as a monetary measurement cannot be a solid decision making criterion for comparing different construction methods. For example, the speed of work offered by modular construction can lead to considerable but indirect cost savings.

The last part of this chapter, reviewed the current studies on the life cycle performance of modular construction. Few studies have been conducted to evaluate the environmental performance of modular buildings by performing life cycle assessment (LCA) analyses. By reviewing these LCA studies, it can be seen that each study focused on a particular aspect of LCA and no comprehensive study was available that enabled comparisons of modular and conventional buildings. For example, some studies focused only on the construction phase, and some quantified and compared limited criteria such as partial embodied energy, among others. One of the reasons behind having fewer and incomprehensive studies could be the fact that the modular construction method is relatively new compared to conventional methods. Therefore, there is limited information and data based on real projects supported by modular homebuilders to perform various analyses.

Due to the rapid global growth of sustainable construction strategies, the continued expansion of new construction techniques such as modular construction highly depends on the quantification of its sustainability and the offered advantages (Lawson and Ogden 2010). Thus, as the findings of the literature review in this chapter showed, effective measurement systems or comprehensive frameworks are needed by which the life cycle sustainability performance of modular buildings with respect to TBL sustainability dimensions can be quantitatively evaluated.

Chapter 4 Identification and Selection of Sustainability Performance Criteria

Parts of this chapter have been published in:

- *Journal of Cleaner Production* entitled “Development of performance criteria for sustainability evaluation of modular versus conventional construction methods” (Kamali and Hewage 2017b).

- *Proceedings of the Modular and Offsite Construction (MOC15) Summit & 1st International Conference on the Industrialization of Construction (ICIC)* entitled “A framework for comparative evaluation of the life cycle sustainability of modular and conventional buildings” (Kamali and Hewage 2015a)

- *Proceedings of the Canadian Society for Civil Engineering International Construction Specialty Conference (ICSC15)* entitled “Performance indicators for sustainability assessment of buildings” (Kamali and Hewage 2015b).

In this chapter, suitable environmental, economic, and social sustainability criteria are identified and ranked for sustainability assessment of residential modular buildings.

4.1 Background

Sustainability is defined as a set of processes aimed at delivering efficient built assets in the long-term (Egan 1998). It is adopting a strategic view of enhancing the impacts of human developments on the environment by satisfying the requirements of people today without undermining the ability of next generations to meet their own needs (Brundtland Commission 1987). As stated before, sustainability considers key TBL dimensions, i.e., environmental, economic, and social, as the main impact dimensions with respect to the above stated developments (WCED 1987).

The built environment and the associated processes significantly influence the TBL dimensions of sustainability (Sev 2009). For example, approximately 40% of the total energy consumption in the US is due to the built environment (Pérez-Lombard et al. 2008; DOE 2008). In Canada, this percentage is 33%, and the built environment also accounts for around 50% of the natural resources consumption (Industry Canada 2011). Traditionally, projects’ specific objectives, such as cost and time, were the primary focus areas of many studies in the past. However, because of the heightened awareness of diverse life cycle impacts of buildings on the environment and society, attention to sustainability has been increasing rapidly and ‘sustainable construction’ has become a significant factor in recent years (Atkinson 1999; Du Plessis 2002; Kandil et al. 2010).

Sustainable construction, whether in relation to new or existing buildings, deals with a variety of proactive processes and strikes a balance between the sustainability dimensions by addressing the associated criteria over the life cycle of a construction project (Douglas 2006).

An optimal construction method selection for each building project has a vital role in achieving the goals of sustainability. According to Wey and Wu (2008), negative environmental and financial impacts, such as resource waste and cost overruns, are the results of choosing inappropriate construction methods. The process of selecting a construction method amongst different options is still made based on anecdotal evidence rather than addressing the life cycle impacts of each option (Pasquire and Gibb 2002; Blismas et al. 2006). Therefore, it is imperative to comparatively assess the life cycle sustainability performance of different construction methods (Kamali and Hewage 2015a).

As far as the sustainability of modular construction is concerned, a literature review in the previous chapter indicated a few studied that assessed the life cycle sustainability performance of modular buildings. However, their main focus was on the environmental sustainability and no comprehensive studies were found on the economic life cycle assessment or social life cycle assessment of modular buildings. It is also important to note that even within the environmental dimension, no studies were found that considered all the life cycle phases and also addressed all aspects of the environmental performance (i.e., environmental impacts and resource conservation) by using all significant criteria. For example, it is difficult to compare the environmental profiles of different construction methods if the comparative assessment is based only on a single life cycle phase or a single (even though widely used) environmental indicator.

The results of the previous studies on life cycle assessment of modular buildings emphasized that the use of modular construction can lead to less environmental impacts compared to traditional construction. However, as mentioned before, in a sustainable building, all applicable TBL sustainability criteria should be sufficiently addressed during the entire life cycle. Setting sustainability goals is important; however, meeting them is more important. According to Douglas (2006), the best way to measure as to whether or not sustainability targets have been met is to use established criteria and indicators. In this research, the most significant step for assessing the life cycle sustainability performance of buildings is to develop suitable sustainability evaluation criteria (SECs) which address the TBL sustainability dimensions. Within each sustainability dimension, there are different areas that can significantly contribute to the overall sustainability of buildings, such as energy, material, cost, and so forth. To evaluate the sustainability of a building, each area can be broken down into a number of assessment criteria, called sustainability performance criteria (SPCs) in this research. For example, ‘material’ can be represented by material consumption, waste management, and so forth. In general, SPCs are employed to assess the sustainability of a product or process. As shown in Figure 4.1, SECs comprise the TBL sustainability categories, i.e., environmental, economic, and social, in which each category includes a number of SPCs associated with different life cycle phases of a building. Each SPC itself can be presented by a number of measurable sub-criteria, called sustainability performance indicators (SPIs). For example, ‘Construction waste management’ is an SPC within the environmental category of sustainability that can include different SPIs such as waste diversion, reuse, and so forth. Note that ‘En.’, ‘Ec.’, and ‘So.’ in Figure 4.1 stand for the environmental, economic, and social dimensions of sustainability, respectively.

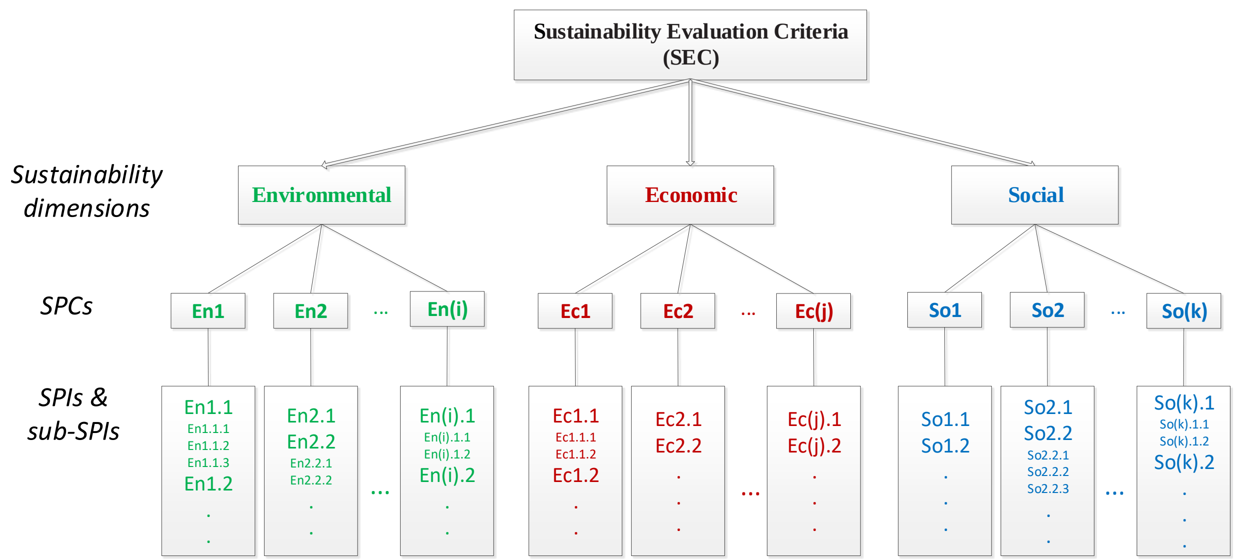

Figure 4.1 The hierarchy of sustainability criteria. Adapted from Kamali and Hewage (2017). Used with permission from © Elsevier

Numerous sustainability assessment criteria and indicators have been reported in the literature for the built environment (Braganca et al. 2010; Chen et al. 2010; Alwaer and Clements-Croome 2010; Mwasha et al. 2011; Pan et al. 2012; Kim and Kim 2016); however, many of them may not be suitable for the subject construction projects in a study. Therefore, to efficiently appraise the sustainability performance of every construction project, first, a set of appropriate SPCs that suit the circumstances of the project, should be identified and selected. Similarly, several criteria have primarily been developed for sustainability evaluation of conventional buildings that should be reviewed in the context of modular buildings. To this end, this chapter identified and ranked the most appropriate SPCs for life cycle sustainability assessment of residential modular buildings.

4.2 Detailed Methodology

The methodical framework used in identification and prioritization of SPCs is presented in Figure 4.2. The methodology in this chapter included different steps. First, the primary potential SPCs under key sustainability dimension categories were compiled. Then, a survey was designed and conducted to capture the construction industry's feedback on applicability of the compiled SPC categories for sustainability assessment of residential modular buildings. Finally, the data collected through the survey was analyzed to rank the SPCs within each sustainability category.

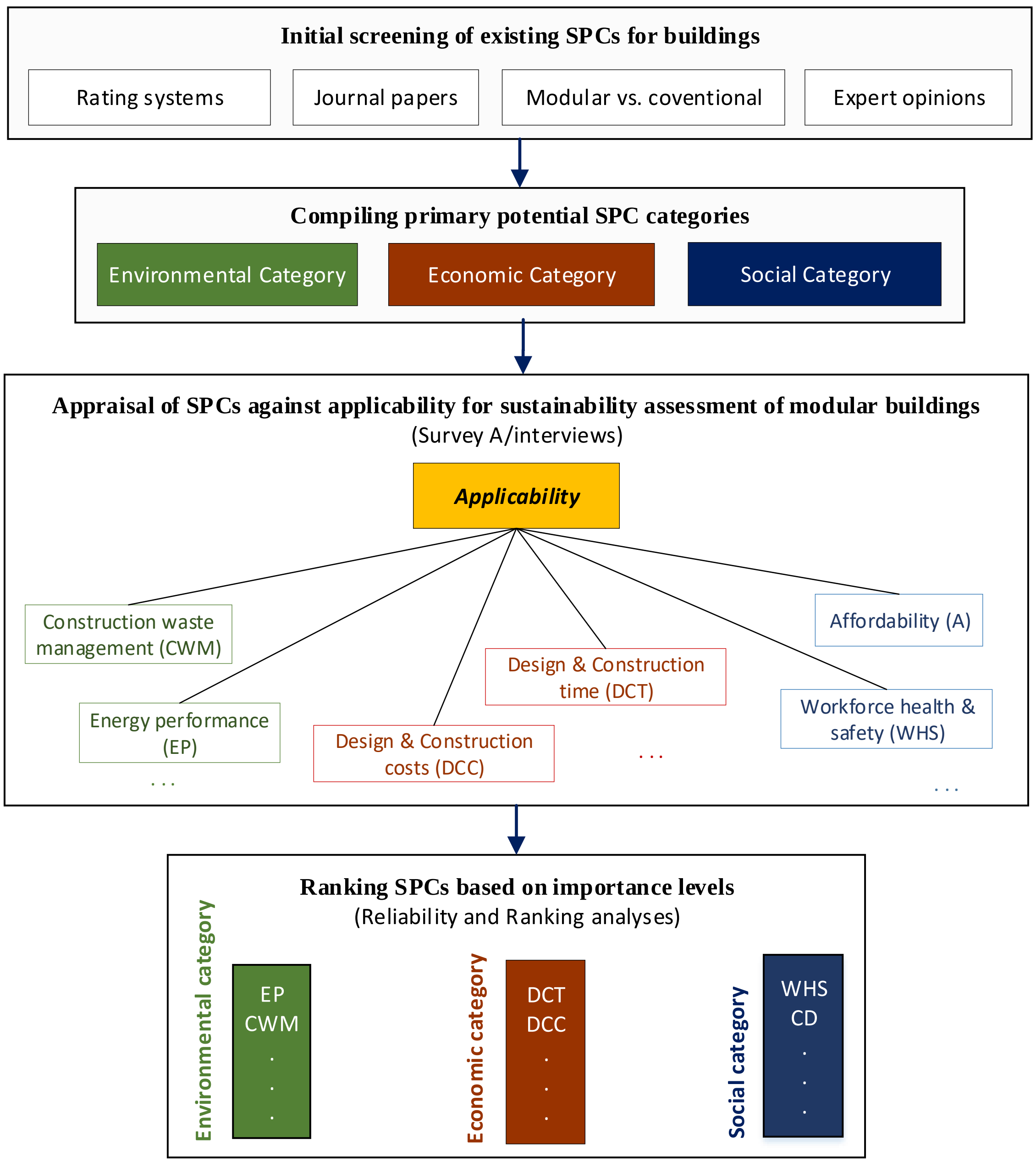

Figure 4.2 Methodology adopted in Chapter 4

4.2.1 SPC Compilation

A list of commonly used SPCs was developed based on a state-of-the-art literature review on the sustainability evaluation of building construction projects as well as experts' feedback. The derived SPCs were categorized into the TBL sustainability categories, i.e., environmental category, economic category, and social category.

4.2.2 Survey Design

In order to identify the most appropriate SPCs for sustainability assessment of a modular building project, the potential SPCs should be evaluated against suitable evaluation criteria. In general, performance criteria/indicators should have the following major characteristics (ADB 2012; Giff and Crompvoets 2008; Lundin and Morrison 2002; Lee 2010; Haider et al. 2014):

- *Applicable*. The criteria should be relevant for performance assessment of a product or process and should address its major aspects and objectives;

- *Adequate*. The criteria should be sufficient to assess the intended function of a product or process. In other words, they should be the minimum number necessary and cost-effective for performance assessment;

- *Understandable*. The criteria should be clear, unambiguous, and easy to understand to all; especially, for those who are not experts;

- *Measurable*. The criteria should be measurable quantitatively or qualitatively in order to facilitate comparisons;

- *Verifiable*. The criteria should be scientifically sound and can be independently verified.

However, depending on the field of assessment, the above list should be carefully refined to choose the most appropriate evaluation criteria for deciding the suitability of SPCs. In this research, 'understandability' of the SPCs has been met by clearly defining and describing them in the screening process. Since the SPC categories were compiled using the literature of residential conventional buildings, their 'applicability' for sustainability assessment of similar modular buildings should be investigated. In the case of 'measurability', the availability and accuracy of the required data for calculation of the SPCs should be checked. As mentioned before, a SPC can be measured by determining suitable measurable SPIs (and sub-SPIs). This means that the measurability of the SPC depends on the measurability of the corresponding SPIs, which have been carefully determined in this thesis (Chapter 5). Similarly, the 'adequacy' and 'verifiability' of each SPC depends on the adequacy and verifiability of the corresponding SPIs. Therefore, the construction experts' feedback on the adequacy, measurability, and verifiability of the compiled SPCs cannot provide certain information in this regard (unless they exactly know each and every SPIs under the SPCs). Therefore, in this research, the suitability of the compiled SPC categories for sustainability assessment of residential modular buildings is evaluated against the ‘applicability’ evaluation criterion only.

In this step, a questionnaire survey, Survey A, was designed to investigate the industrial perceptions and expectations on the sustainability criteria that are suitable (applicable) for performance assessment of modular versus conventional buildings. Description of the ‘applicability’ evaluation criterion used in the questionnaire was as follows:

Applicability: How important and relevant is the SPC when assessing the sustainability of modular versus conventional buildings?

Survey A was designed using the compiled SPC categories. In order to provide the survey participants an easy to use and interactive environment, the Adobe LiveCycle Designer survey design tool was used. The survey’s purpose, benefits, duration, confidentiality, guidance on completion, contact information, and consent form were provided in the first page of the questionnaire. Two major sections were then included in the questionnaire. The first section concerned the potential respondent’s profile information, such as the profession, the years of experience, and the nature of the organization. In the second section, the derived TBL SPCs along with a clear description of each SPC were listed and the respondent was asked to outline his/her view by scoring the applicability (importance) of each SPC when comparing the sustainability of modular and conventional construction methods. In other words, depending on the capability of each SPC for making a difference in the sustainability of these two construction methods, the construction professionals’ opinions were captured using a 5-point ordinal Likert scale ranging from ‘Very Low’ to ‘Very High’. Point 1 (i.e., ‘Very Low’) meant the given SPC is the least important, hence it can make a minor difference or none when the two method’s sustainability is compared. Conversely, point 5 (i.e., ‘Very High’) was considered as extremely important, and the SPC has significantly different values/amounts in each construction method. At the end of the questionnaire, respondents were asked to suggest any supplementary criteria if they were not already mentioned in the SPC list.

4.2.3 Survey Implementation

First, the survey potential participants were identified. Key construction practitioners, such as architects, engineers, construction managers, and manufacturers, as well as academically affiliated experts (who were originally engineers/architects) were considered as the potential participants for Survey A and informal interviews. These experts had experience in both modular and conventional building projects. The main focus of the research was on the US and Canadian construction industry.

In this research, direct and indirect methods were used to contact the potential participants. Under the indirect contact method, modular industry related organizations (e.g., associations/institutions) were searched to ask for participation in the survey by distributing the questionnaire to their members. The Modular Building Institute (MBI) helped to contact the potential respondents. Founded in 1983, the MBI is the international non-profit trade association serving modular construction. MBI members are manufacturers, contractors, engineers, architects, and dealers (MBI 2014). In addition, the 2015 MOC & 1st ICIC conference planning committee was asked for their assistance. In the case of the direct contact method, a list of construction practitioners and academically affiliated experts, who have been involved in both modular and conventional construction processes, were identified and included in the potential participants list.

Upon completion of the contact list, the questionnaire was disseminated to the above potential respondents, either by delivering online (i.e., emailing the interactive version), or delivering offline (i.e., distributing the paper version). After all the questionnaires were delivered, two follow up reminders were sent. In addition, a number of experienced participants were selected and interviewed during the 2015 MOC & 1st ICIC conference to obtain deeper understanding of the survey results and the rationale behind the SPCs scoring.

4.2.4 Methods of Data Analysis

After receiving all the completed forms, the next critical step was to analyze the collected data. In this research, two standard analyses, i.e., reliability analysis and ranking analysis that have been used in many previous studies were chosen for data analysis. These methods were found suitable for determining the applicability of sustainability criteria when two products or processes, e.g., two construction methods, are compared (Chen et al. 2010).

Reliability analysis is used to examine how well different items (here SPCs) in a questionnaire measure the same concept. This analysis was performed to test the reliability of Survey A. To this end, Cronbach's alpha measure, also named the reliability coefficient, was used to verify how closely the derived sustainability criteria (SPCs) used in the questionnaire relate to each other. The value range of Cronbach's alpha is between 0 and 1, in which the greater values indicate higher internal consistency reliability of the SPCs. According to Nunnally (1978), reliability coefficients greater than 0.70 are considered as acceptable. To calculate Cronbach's alphas, Statistical Package for Social Sciences (SPSS) was used.

Subsequently, the collected data was analyzed using the ranking analysis to rank the developed

SPCs. As mentioned earlier, in this study a 5-point ordinal Likert scale was used to score the importance (applicability) of SPCs. In ordinal scales, scoring is based on the rank order of criteria and the exact difference between two points is not known. For example, point 4 is more important than point 3; however, it cannot be quantified exactly how much more important. According to Johnson and Bhattacharyya (1996), when using descriptive statistics (e.g., Likert scales), non-parametric methods should be used to rank the items rather than parametric statistics (means, standard deviations, etc.). Therefore, the Severity Index (SI) method was used to rank the SPCs according to their applicability (importance) since the scoring system was ordinal in nature. The SI is calculated as (Idrus and Newman 2002):

$$\text{Severity Index (SI)} = \frac{\left(\sum_{i=1}^{5} w_i \cdot \frac{f_i}{n} .100\%\right)}{a} \qquad [4.1]$$

where i is the score of each SPC ranging from 1 to 5 assigned by the survey respondents; w_i is the weight of the assigned score (1 is the least important and 5 is the extremely important); f_i is the total frequency of the score i; n is the total number of the completed questionnaires; and a is the highest weight which is 5 in this survey. SI values ranged between 0 and 100%.

In this procedure, the frequency analysis was first carried out to obtain the percentage ratings of the different selection factors. This was performed with the help of SPSS. The percentage ratings (given as 'valid percentage' by SPSS) were then used to calculate the severity indices via the above equation. The term $f_i \,.100\%/n$ is the valid percentage as calculated by SPSS.

All the SPCs were ranked (based on their severity index values) under the overall TBL SPCs (i.e., all 32 SPCs) as well as within each associated sustainability dimension categories, i.e., the environmental category, the economic category, and the social category. Subsequently, each SPC was assigned an importance level according to the following severity scale:

- Extremely High (EH): $SI \geq 95.00\ \%$
- Very High (VH): $85.00\ \% \leq SI < 95.00\ \%$
- High (H): $75.00\ \% \leq SI < 85.00\ \%$
- Medium (M): $65.00\ \% \leq SI < 75.00\ \%$
- Low (L): $55.00\ \% \leq SI < 65.00\ \%$
- Very Low (VL): $45.00\ \% \leq SI < 55.00\ \%$
- Extremely Low (EL): $SI < 45.00\ \%$

Those SPCs that were assigned as either 'Extremely High', 'Very High', 'High', or 'Medium' by the participants were considered as the critical sustainability criteria. In other words, they were considered potential criteria that are capable of making a considerable difference between the sustainability of modular and conventional buildings.

4.3 Sustainability Performance Criteria

As mentioned above, a comprehensive literature review, five interviews, and the results of Chapter 3, were analyzed to develop appropriate TBL SPCs and to be included in Survey A. A content-analysis based literature review was conducted to develop the most commonly used TBL sustainability criteria for residential buildings. Content analysis is a qualitative type of document analysis, which is a systematic method to review and evaluate different documents. In other words, content analysis is the process of collecting and organizing information related to the primary research questions (Bowen 2009). Holsti (1969) provided a broad definition of content analysis as, "any technique for making inferences by objectively and systematically identifying specified characteristics of messages". All forms of documents, including electronic and printed, such as letters, books, survey reports, organizational papers, advertisements, and so forth, can be used as references (Holsti 1969).

First, a preliminary list of building sustainability criteria was developed based on the review of the following source categories:

1- The sustainable building rating systems (simply called rating systems) that are mainly intended to be used internationally, such as LEED (Leadership in Energy and Environmental Design), Green Globes, BREEAM (Building Research Establishment Environmental Assessment Method), LBC (Living Building Challenge), among others. Rating systems that were developed to assist in the management of “green” or “environmentally friendly” building projects have a vital role in informing on progress in sustainability practices (Siew et al. 2013). As described in the previous chapter, rating systems are good examples of sustainability assessment systems that mostly deal with the environmental sustainability of buildings by providing a set of performance criteria and scoring each building project based on those criteria. Rating systems examine the performance of a “whole building” and allow comparison of different buildings (Fowler and Rauch 2006; Smith et al. 2006).

2- Other published literature related to sustainable construction and sustainability of buildings. This source category included published journal and conference papers that provided and discussed relevant sustainability criteria for one or more sustainability dimensions. The University of British Columbia (UBC) library databases, Compendex Engineering Village, and American Society of Civil Engineers (ASCE), were used to retrieve the appropriate journal and conference articles. Key words used were combinations of: ‘building’, ‘sustainability’, ‘performance’, ‘life cycle’, ‘indicator’, ‘criteria’, ‘evaluation’, and ‘assessment’. These articles were further refined by reviewing abstracts and conclusions.

Through the reviewing and screening processes, in the first round of screening, a long list of sustainability criteria were developed regardless of their sustainability dimensions, terminologies, and relationships. In the second round, attention paid to criteria’s sustainability dimensions; therefore, they were placed in the correct sustainability category (i.e., either environmental, economic, or social). Through the third round, those criteria with the same meaning but different terminology were merged into a one criterion. Then, those criteria that had relationships or overlaps were combined or modified. In this regard, a number of main criteria (i.e., SPCs) were developed in which other criteria can be represented under them. The final step was to narrow the SPC list down by identifying the frequency of each SPC in the reviewed literature. To refine the SPC list, the instructions below were applied to further refine the SPC list (Kamali and Hewage 2015b):

- Environmental dimension: Rating systems were intended to mainly address the environmental performance of buildings. Moreover, they were developed based on many academic and industry experts’ opinions. Therefore, more attention was paid to the rating systems than journal/conference articles. In this regard, if a SPC was used in more than half of the reviewed rating systems, the SPC is selected regardless of its frequency in the second source category (i.e. journal/conference articles). If not, the frequency count in all references, including the rating systems and articles, should be more than 50% in order for a SPC to be selected.
- Economic and social dimensions: Despite the many studies about the environmental performance, few studies addressed the economic and social performance of buildings. Therefore, if the frequency count of a SPC in all documents, including the rating systems and articles, was more than 20%, the SPC is selected.

In addition, in the development of questionnaire, five academic researchers were provided with the compiled SPC categories and their feedback was received. Eventually, based on the literature reviews conducted in this chapter and Chapter 3 and also the interviews, the final developed TBL sustainability criteria including 11 environmental SPCs, 9 economic SPCs, and 12 social SPCs, were incorporated into Survey A. Table 4.1 lists the final TBL SPCs along with their acronyms.

Table 4.1 Primary potential sustainability performance criteria developed in this research

Environmental SPCs	Economic SPCs	Social SPCs
Site selection (SS)	Design and construction time (DCT)	Health, comfort, and well-being of occupants (HO)
Alternative transportation (AT)	Design and construction costs (DCC)	Influence on the local economy (ILE)
Site disruption and appropriate strategies (SD)	Operational costs (OC)	Functionality and usability of the physical space (FU)
Renewable energy use (RE)	Maintenance costs (MC)	Aesthetic options and beauty of building (ABB)
Energy performance and efficiency strategies (EP)	End of life costs (EC)	Workforce health and safety (WHS)
Water and wastewater efficiency strategies (WE)	Durability of building (DB)	Community disturbance (CD)
Regional (local) materials (RM)	Investment and related risks (IRR)	Influence on local social development (ISD)
Renewable and environmentally preferable products (REP)	Adaptability of building (AB)	Cultural and heritage conservation (CHC)
Construction waste management (CWM)	Integrated management (IM)	Affordability (A)
Greenhouse gas emissions (GE)		Safety and security of building (SSB)
Material consumption in construction (MCC)		User acceptance and satisfaction (UAS)
		Neighborhood accessibility and amenities (NAA)

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In this research, it was assumed that the compiled SPCs are independent of one another. However, there are interrelationships between some of them. For example, while the 'Construction waste management' was placed in the environmental SPC category, it has also economic implications. The detailed interrelationships between the SPCs and the associated indicators (Chapter 5) can be studied using different methods that allow consideration of the interdependence of criteria and indicators, such as the analytic network process (ANP) method. However, such study itself requires extensive data collection, which was beyond the scope of this research.

4.4 Ranking the TBL Sustainability Performance Criteria

Results made during this research were used to deduce the current construction industry's perceptions of the key sustainability criteria for life cycle sustainability performance assessment of residential modular buildings to rank and select the most 'applicable' SPCs. It should be mentioned that, to examine the construction experts' perceptions on the 'measurability' of the SPCs and the impact of its inclusion (in addition to 'applicability') on the SPCs' rank orders, a supplementary study was conducted. This supplementary study conducted additional surveys to evaluate the SPCs against both ‘applicability’ and ‘measurability’, and employed the Analytic Hierarchy Process (AHP) and the Elimination and Choice Translating Reality (ELECTRE) MCDA methods to analyze the surveys and rank the SPCs (see Appendix A for details). When comparing the results of investigating the ‘applicability’ only, with the results of investigating both the ‘applicability’ and ‘measurability’, it was evident that the rank order of some SPCs have been changed locally but the overall trend remained the same in both studies. As discussed earlier, the ‘measurability’ of the complied SPCs are ensured in the next chapter when determining suitable measurable SPIs under each selected SPC. Therefore, the empirical evidence from the study of ranking the SPCs based on their applicability only was reported in this section.

4.4.1 Survey Respondents

A total number of 51 experts responded to the research participation requests, i.e., the initial invitation and two follow-up reminder emails. Among the received questionnaire forms, 46 completed forms were properly filled out and returned; therefore, they were included in the analyses. In addition, the survey overall response rate including direct and indirect questionnaire delivery contact methods, was 21.9% (Table 4.2).

Table 4.2 Survey dissemination details and the rate of valid responses

Contact method	No. of delivered forms	No. of received forms	No. of valid forms	Response rate (%)
Indirect	134	14	13	9.7
Direct	76	37	33	43.4
Total	210	51	46	21.9

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There are two primary variables of measurement: (1) Continuous, and (2) Categorical. For example, if a researcher plans to use a seven-point scale to measure ‘job satisfaction’ or the extent to which the respondents are agreed with a phrase, these are continuous variables. In contrast, if the researcher wants to determine if the respondents differ by gender or educational level, these are certain categorical variables (Bartlett et al. 2001). For each type of measurement variables, a sample size calculation formula was proposed by Cochran (1977). In this research, since the applicability of the TBL SPCs was measured, the measured variables are continuous as opposed to categorical and a five-point Likert scale was used for measurement. Therefore, the Cochran’s formula for continuous variables that has been used in many studies (e.g., Antar 2012; Karami et al. 2015; Sushi et al. 2016, among others) was used to determine the adequate sample size in this survey:

$$n = \frac{z^2_{\alpha/2} * s^2}{d^2} \qquad [4.2]$$

where *n* is the sample size.

$z_{\alpha/2}$= confidence coefficient for the selected confidence level (1-α) and associated alpha level (α) in each tail. The alpha level indicates the level of risk the researcher is willing to take that true margin of error may exceed the acceptable margin of error.

s = estimate of the standard deviation in the population.

d = acceptable margin of error for mean (*d* = number of points on primary scale × error researcher is willing to except).

According to the literature, the commonly used confidence levels are 90% and 95%. In addition, a commonly acceptable value for the margin of error is 5% (Olson and Kellogg 2014; Méda et al. 2014; Ferguson and Takane 1989). In this study, the confidence level was initially set at 90% (i.e., $\alpha/2$ = 5% and $z_{\alpha/2}$ = 1.64) and the acceptable margin of error was selected as 5%. However, the final sample size was good enough to make conclusions with 95% confidence level as explained below.

According to Bartlett et al. (2001) a critical component of sample size formulas is the estimation of the standard deviation in the primary variables of interest in the study. The researcher does not have direct control over the standard deviation and must incorporate variance estimates into research design. Cochran (1977) listed four strategies of estimating population variances for sample size determinations: (1) take the sample in two steps, and use the results of the first step (i.e., the variance observed in the first step data) to determine how many additional responses are needed to attain an appropriate sample size; (2) use a pilot study results; (3) use data from previous studies of the same or a similar population; or (4) estimate or guess the structure of the population assisted by some logical mathematical results. In this study, the first strategy was adopted, which provided early indications on the needed sample size. In the first step, 13 completed questionnaires were taken and the standard deviations of the respondents' scores for all the TBL SPCs were calculated. The results revealed that the standard deviations ranged between 0.51 and 0.96. Appendix B provides the collected data in the first step study and corresponding standard deviations. Therefore, using Equation [4.2], the required sample size *n* was obtained between $n = \frac{1.64^2 * 0.51^2}{(5*0.05)^2} = 11.19$ and $n = \frac{1.64^2 * 0.96^2}{(5*0.05)^2} = 39.65$. By rounding these values up to their next highest integer, the minimum required sample size to assess the selected SPCs came to be between 12 and 40. In other words, certain SPCs had relatively low standard deviation in the first step study, which required low sample size. Hence, a minimum sample size of 40 is acceptable to draw conclusions out of all the SPCs. This minimum sample size was calculated based on the confidence level and the margin of error of 90% and 5%, respectively. However, Cochran's sample size calculation and correction formulas (Bartlett et al. 2001) revealed that, even with a more precise confidence level (i.e., 95%), the sample size of 46 valid questionnaires is adequate to be used in the analyses.

The first main section of the questionnaire searched for the respondent's background information. The participants were affiliated with diverse types of organizations (mainly in North America), e.g., engineering companies, modular manufacturers, general contractors, academic institutions, among others. The number of employees in the organizations were also different. For instance, 43% of the organizations had at least 500 employees. The participants were also from different professions. For example, 9 completed forms were received from construction managers, 6 from engineers, 4 from architects, 16 from academic researchers (originally engineers/architects), and so forth. A number of respondents had rich experience in two or even more professions. In addition, the survey participants had different years of professional experience, ranging from 5 (and fewer) to over 35. While only below 7% of the respondents were younger industry practitioners with less than 5 years of experience, 32% had between 5 and 15 years, 36% had between 16 and 30 years, and 25% had over 30 years professional experience as indicated in Figure 4.3 The respondents' involvement in modular building projects were also sought in order to examine the extent to which the respondents were familiar with modular processes. The questionnaire data showed that most of the experts have been involved in a number of modular building projects. For example, 25% of them had contributed to over 55 modular projects.

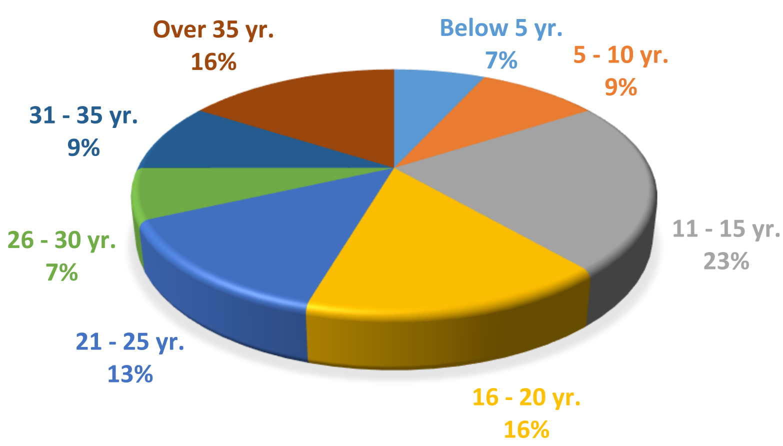

Figure 4.3 Professional experience of the survey participants. Reproduced from Kamali and Hewage (2017b). Used with permission from © Elsevier

The number of respondents, along with their diverse professions, organizations, professional experience, and history of involvement in both modular and conventional building projects ensured that the results of this survey can adequately represent the construction industry's feedback.

4.4.2 Reliability Analysis

As stated in the methodology section, a reliability analysis was conducted to examine the internal consistency of Survey A. The data collected through the completed forms was fed into the SPSS software as input and four rounds of reliability analyses were performed. The analyses included one analysis that considered all SPCs as a whole set of sustainability criteria (overall TBL SPCs), and three independent analyses that separately considered the SPCs associated with the sustainability categories (i.e., environmental, economic, and social). As discussed previously, a minimum reliability coefficient of 0.70 ensures that adequate internal consistency of a test exists. The resulted Cronbach's alpha values are shown in Table 4.3, which are much higher than the minimum reliability coefficient recommended by Nunnally (1978). The reliability coefficient values for the overall TBL SPC set, environmental SPC set, economic SPC set, and social SPC set indicate strong internal consistency of Survey A.

Table 4.3 Reliability coefficients for different SPC categories

Sustainability category	SPC count	Cronbach's alpha
Environmental	11	0.899
Economic	9	0.837
Social	12	0.883
Overall TBL SPCs	32	0.944

4.4.3 Environmental Criteria Ranking

Similar to the reliability analysis, four rounds of ranking analyses were conducted to analyze the data collected through Survey A. Based on the output of the SPSS software (i.e., valid percentage values) and Equation [4.1], severity index (SI) values were obtained. These SI values were used to identify the rank of all the SPCs under the overall TBL SPCs as well as within their associated sustainability categories. According to the SI value of a SPC, its importance level was assigned using the severity scale defined earlier ranging from 'Extremely High' to 'Extremely Low'.

It is worth to mention that to ensure the validity of the SPC rankings based on their SI values, the collected data was analyzed one more time using the ELECTRE MCDA method (see Appendix A for the step-by step procedure of the ELECTRE method). The results of the ELECTRE analyses showed identical rank orders for SPCs in all the three sustainability categories.

The overall rank order of each SPC within the environmental category is shown in Table 4.4. All of the environmental SPCs were assigned as ‘High’ to ‘Medium’ importance, except three SPCs. As Table 4.4 illustrates, there was no ‘Extremely High’ and ‘Very High’ level SPCs; however, 4 SPCs were ranked ‘High’ level criteria with SI values ranging from 76.10% to 81.47%. These highly addressed criteria included ‘Construction waste management’, ‘Energy performance and efficiency strategies’, ‘Material consumption in construction’, and ‘Greenhouse gas emissions’.

Table 4.4 Ranking of the environmental sustainability performance criteria

Environmental category	SI (%)	Rank in category	Rank in overall TBL SPCs	Level of Importance
Construction waste management (CWM)	81.47	1	6	H
Energy performance and efficiency strategies (EP)	80.96	2	7	H
Material consumption in construction (MCC)	79.58	3	8	H
Greenhouse gas emissions (GE)	76.10	4	13	H
Site disruption and appropriate strategies (SD)	73.66	5	19	M
Renewable and environmentally preferable products (REP)	70.73	6	22	M
Regional (local) materials (RM)	67.33	7	24	M
Renewable energy use (RE)	66.90	8	25	M
Site selection (SS)	63.35	9	28	L
Water and wastewater efficiency strategies (WE)	62.44	10	29	L
Alternative transportation (AT)	52.76	11	32	VL

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The most significant criterion among the top prioritized environmental SPCs was ‘Construction waste management (CWM)’ (*SI* = 81.47%) which was also considered as highly ranked criterion in the overall TBL SPCs (6th among all 32 SPCs). Supporting this, the literature reveals that modular construction has the potential capability of providing more efficient waste management strategies, contrary to conventional construction. In other words, modular construction has shown better waste management results in terms of control (reduce), reuse, recycle, and waste disposal in manufacturing centers (Zenga and Javor 2008; Kawecki 2010; Cartz and Crosby 2007). For example, materials can be precisely cut in modular factory environments, which results in less construction waste. Furthermore, in modular construction, different modules have the capability to be used in new building projects by disassembling, relocating, or refurbishing them at the end of life phase of buildings, compared to conventional buildings where a considerable amount of generated waste is sent directly to landfills (Li and Li 2013). However, because the fabricated modules need to be safely transported to the final project sites, in order to fulfill the “required structural strength” for transportation, around 10-15% additional materials are used (in interface such as walls) compared to traditional construction (Cameron and Di Carlo

2007). This is probably why the respondents concerned about the ‘Material consumption in construction (MCC)’. While the construction waste can be reduced when using modular construction, additional materials are used for structural integrity and also when transporting the modules to the final building location.

The second ‘High’ importance level SPC highlighted by the respondents was ‘Energy performance and efficiency strategies (EP)’, with a SI value very close to the first ranked SPC. It was also ranked 7th among all the TBL SPCs. The literature shows that the occupancy phase is the dominant phase in terms of environmental impacts (Quale et al. 2012; Scheuer et al. 2003; Sartori and Hestnes 2007) with over 70% of the total energy consumption (Ortiz et al. 2009; Scheuer et al. 2003; Keoleian et al. 2000). Having access to more efficient technologies, buildings are becoming more energy efficient over their operation phase. Consequently, other life cycle phases, such as the construction phase and the end of life phase are growing in importance (Gustavsson and Joelsson 2010). However, the use phase still is prevailing in terms of energy consumption and environmental impacts. Two reasons may be offered as to why the respondents chose ‘Energy performance and efficiency strategies’ as one of the most important SPCs: i) the overall importance of energy efficiency in the use phase of a building, and ii) the modular and conventional buildings’ dissimilar designs and installations of operational energy efficiency systems, e.g., insulation and quality of construction in factory environment.

As discussed in Chapter 3, modular and conventional buildings are mainly different in their design and construction phases. Therefore, the ‘Greenhouse gas emissions (GE)’, which represents the environmental impacts of the construction process, was observed among the ‘High’ important SPCs.

In the bottom of Table 4.4 the ‘Low’ or ‘Very Low’ important SPCs were located including ‘Site selection’, ‘Water and wastewater efficiency strategies’, and ‘Alternative transportation’. The construction experts believed that there is no significant difference between modular and conventional buildings with respect to these SPCs; therefore, they assigned the lowest scores to these SPCs among all the environmental SPCs. The low ranks of ‘Site selection’ and ‘Alternative transportation’ was anticipated because these criteria are mainly related to the building location and are not dependent on the construction method by which the building is constructed. Noticeably, ‘Alternative transportation’ was also rated as the least important criterion (32nd) among all the TBL SPCs.

4.4.4 Economic Criteria Ranking

The outcomes resulting from the ranking analysis of the economic criteria are reflected in Table

4.5. Based on the values of the severity indices, among the nine SPCs in the economic category, two SPCs, four SPCs, and three SPCs placed in the 'Very High', 'High', and 'Medium' levels, respectively.

The first top ranked ('Very High') economic SPC, as anticipated, was 'Design and construction time (DCT)' with the SI value of 87.24%. This SPC was ranked second under the overall TBL SPCs, which indicates the importance of this criterion among all the SPCs as well. These results are consistent with the findings of Chen et al. (2010). As reported in Chapter 2, a significant difference between the modular and conventional construction methods is the fast turnaround between the breaking of ground and occupancy in the case of the former method. Unlike the conventional processes, construction of a building (manufacturing modules) and preparation of the final project site (foundations, etc.) can be performed simultaneously (Kawecki 2010; Haas et al. 2000), which can lead to approximately 40% savings in the construction time (Mah 2011; Lawson and Ogden 2010; Smith 2011; MBI 2012a). The resulted time savings can greatly contribute to project cost savings when using modular processes. In other words, speed of construction can enhance the economic positive impacts since the developers/contractors can rapidly deliver the finished buildings to end users (clients or potential buyers) and start new projects. On the other hand, the end users can occupy their buildings faster and eliminate unnecessary expenses such as rental. Furthermore, this can help the economy of the community the buildings are built.

Table 4.5 Ranking of the economic sustainability performance criteria

Economic category	SI (%)	Rank in category	Rank in overall TBL SPCs	Level of Importance
Design and construction time (DCT)	87.24	1	2	VH
Design and construction costs (DCC)	86.38	2	3	VH
Durability of building (DB)	78.52	3	9	H
Integrated management (IM)	77.56	4	10	H
Investment and related risks (IRR)	77.09	5	11	H
Operational costs (OC)	76.06	6	14	H
Adaptability of building (AB)	74.76	7	16	M
Maintenance costs (MC)	74.52	8	17	M
End of life costs (EC)	66.36	9	26	M

The next major economic concern of the respondents was 'Design and construction costs' (*SI* = 86.38%). This SPC was found to be at 3rd rank under the overall TBL SPCs. As shown in Table 4.5, the costs associated with the design and construction phase of a building, such as design, coordination, materials, and labor, grabbed the attention of the respondents more than the costs associated with the other life cycle phases. The possible reason could be the costs associated with the initial phases of a building’s life cycle can be perceived as short-term costs; therefore, they are more perceptible (tangible) costs. Interestingly, the costs related to the end of life phase are long-term costs and rated as the least important SPC under the economic category (with SI value of 66.36), even though it is still a ‘Medium’ importance level criterion. Accordingly, it can be observed from Table 4.5 that ‘Operational costs’ and ‘Maintenance costs’, which are both mid-term costs, were assigned close SI values and located somewhere between ‘Design and construction costs’ and ‘End of life costs’.

Although some literature pointed out that the economic impacts of using off-site construction methods are not evident (Chiang et al. 2006; Pan et al. 2011; Lawson and Ogden 2008), there are various attributes that can lead to cost savings when these methods are used (Haas et al. 2000; Lawson et al. 2012). Moreover, the cost reduction spots can be different in different life cycle phases of a building. For example, due to concurrent fabrication of several modules, less workforce and machinery transportation are needed. In addition, the required materials are purchased in bulk and therefore less expensive (Chiu 2012).

The modular construction can effectively influence the other SPCs from the economic point of view, such as ‘Durability of building’. The modular construction method offers higher quality than the traditional counterpart due to controlled manufacturing environment (Cartz and Crosby 2007; Rogan et al. 2000). Furthermore, higher finished building quality can be achieved due to “less material exposure to harsh weather” on the final project site. In addition, high quality, lightweight, and durable materials are utilized in the construction of each module itself (O’Brien et al. 2000; Celine 2009; Cartwright 2011; Haas and Fagerlund 2002). Moreover, as mentioned before, extra materials are used in building interface (mostly walls) to ensure the structural integrity of the whole buildings when connecting the modules on the final project site. All of these can yield greater durability of modular buildings.

4.4.5 Social Criteria Ranking

Results of the final preferences for the SPCs within the social category are presented in Table 4.6. Among the twelve social SPCs, only three SPCs were rated either ‘Very Low’ or ‘Low’, while nine SPCs were placed in either ‘Medium’, ‘High’, or ‘Very High’ importance levels. Noticeably, the top three social criteria were also among the top five overall TBL SPCs, which implies the construction industry’s increased perception of the role of social criteria in the overall sustainability of different construction methods.

The ‘Construction workforce health and safety’ SPC was the only criterion that was ranked first among both the overall TBL SPCs and the category it belonged to (i.e., social category). This

SPC was a ‘Very High’ importance SPC with an impressive SI value of 91.25%, which was higher than the SI values of the top ranked economic and environmental SPCs. This indicated the significance of the health and safety of the workers to the overall sustainability of a building from the construction experts’ perspectives, and pointed to their belief that the modular and conventional processes can provide extremely different degrees of labor health and safety in building projects. As stated in the previous chapter, on-site reportable accidents can be decreased up to 80% using off-site construction processes (Lawson et al. 2012). By performing the main work in manufacturing centers (rather than on the final project sites) working at height, dangerous activities, severe weather, congestion, workplace accidents, and neighboring construction operations can be decreased (McGraw-Hill Construction 2011; Na 2007; Li et al. 2013; Haas and Fagerlund 2002).

It is a significant observation that ‘Construction workforce health and safety’ was of paramount importance to the respondents; however, ‘Health, comfort and well-being of occupants’ is not. Even though the latter was recorded as ‘Medium’ importance criterion, which shows this SPC is a relatively important one, its rank within the social category is not as high as expected.

Table 4.6 Ranking of the social sustainability performance criteria

Social category	SI (%)	Rank in category	Rank in overall TBL SPCs	Level of Importance
Workforce health and safety (WHS)	91.25	1	1	VH
Community disturbance (CD)	83.45	2	4	H
Safety and security of building (SSB)	81.92	3	5	H
User acceptance and satisfaction (UAS)	76.56	4	12	H
Affordability (A)	75.14	5	15	H
Functionality and usability of the physical space (FU)	74.12	6	18	M
Influence on the local economy (ILE)	73.11	7	20	M
Aesthetic options and beauty of building (ABB)	72.64	8	21	M
Health, comfort, and well-being of occupants (HO)	70.22	9	23	M
Influence on local social development (ISD)	64.47	10	27	L
Neighborhood accessibility and amenities (NAA)	60.06	11	30	L
Cultural and heritage conservation (CHC)	53.06	12	31	VL

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The SPC named ‘Community disturbance’ was ranked second and fourth under the social category and the overall TBL SPCs, respectively. The respondents believed that there is an enormous difference between modular and traditional construction in terms of minimizing the social impacts of on-site construction activities on the project site and surrounding local communities, which can be justifiable according to the literature. As mentioned previously, when using modular construction, the majority of the project work (85-90%) is performed in manufacturing centers (Kawecki 2010). Thus, construction noise, dust, light pollution, traffic congestion (due to materials, machinery, and workforce transportation) are reduced significantly, resulting in less community disturbance.

When the results of all ranking analyses (Tables 4.4 to 4.6) were simultaneously evaluated for the environmental, economic, and social categories, the 32 TBL SPCs were assigned importance levels as shown in Figure 4.4. According to the SI values, no SPC was rated as 'Extremely High' or 'Extremely Low' importance.

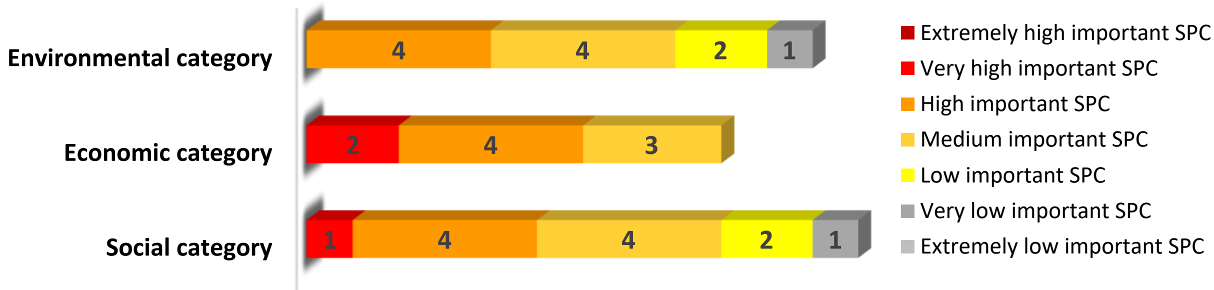

Figure 4.4 Number of TBL SPCs assigned each of the importance levels. Reproduced from Kamali and Hewage (2017b). Used with permission from © Elsevier

It should be emphasized that, as some respondents asserted, 'Very Low' or 'Low' importance rankings for a SPC does not mean that it is not important by itself, but rather it means there is no considerable difference in that SPC between modular and conventional construction methods. In other words, this SPC cannot significantly contribute to comparatively assessing and distinguishing the overall sustainability of the two construction buildings.

It can be understood from the construction industry experts' feedback that the social and economic criteria play more important roles than the environmental ones when the sustainability of modular construction versus traditional construction is concerned. This was investigated from two different approaches; considering the top ranked SPCs within the overall TBL SPCs and comparing the SI value averages of the 'High' and 'Very High' important SPCs within each sustainability dimension category. According to Tables 4.4 to 4.6, among the top 5 SPCs in the overall TBL SPCs, the first, fourth, and fifth belong to the social category and the second and third belong to the economic category, while the top ranked SPC within the environmental category ranked sixth in the overall TBL SPCs. In addition, using the second approach, the average SI values within the 'Very High' and 'High' importance SPCs for the social category, the economic category, and the environmental category, have been 81.66%, 80.48 %, and 79.52%, respectively, which also supports the above idea.

Furthermore, comparison of the relative frequency of 'Very High' and 'High' level SPCs in each sustainability dimension category demonstrated the fact that among the TBL sustainability dimensions, the economic dimension was still the governing concern of the construction industry practitioners (even though the top SPC within the overall TBL SPCs is a social one) followed by the social dimension. Approximately 67% of the economic criteria were rated as ‘Very High’ and ‘High’ importance, which was noticeable compared to the cases of social and environmental criteria (42% and 33%, respectively). In addition, when the total SI value averages (regardless of the importance levels of SPCs) of the three sustainability dimension categories were compared, again, the economic dimension (SI average=78%) was superior to both cases of the social dimension and environmental dimension.

4.4.6 Effect of Professional Experience on Ranking Results

As stated, the data collected through the survey showed that the research participants had diverse professional characteristics, such as the number of employees in their firms, professional experience, and history of involvement in modular projects. Thus far, all the analyses were conducted based on the assumption that the opinions of the research participants were equally important, regardless of their different profile characteristics. That is, all respondents’ feedback had equal weight when conducting different analyses. For example, a respondent’s opinion with 5 years of professional experience and a respondent’s opinion with over 35 years were considered equal. Among the diverse profile characteristics of the respondents, some can have an impact on the results, but some cannot. For example, the number of employees in the organization in which a respondent belongs cannot necessarily guarantee the robustness of his/her opinions as there are many knowledgeable experts working in small firms, and vice versa.

In this research, professional experience, as one of the respondents’ profile characteristics that potentially can influence the results, was further investigated. The participants were divided into two groups including experts with less or equal than 20 years and experts with over 20 years of professional experience. The first group included 25 junior to highly experienced experts and the second group included 21 extremely high (i.e., associate) experts. Figure 4.5 illustrate the results of the ranking analysis for these two groups of participants within the environmental, the economic, and the social categories, respectively. Furthermore, in each case, the previous results, where all of the respondents’ opinions were considered equal, are shown for easier comparisons.

An impressive consistency can be found out when comparing the social SPC rankings by all respondents with respondents with less than 20 years of experience and respondents with over 20

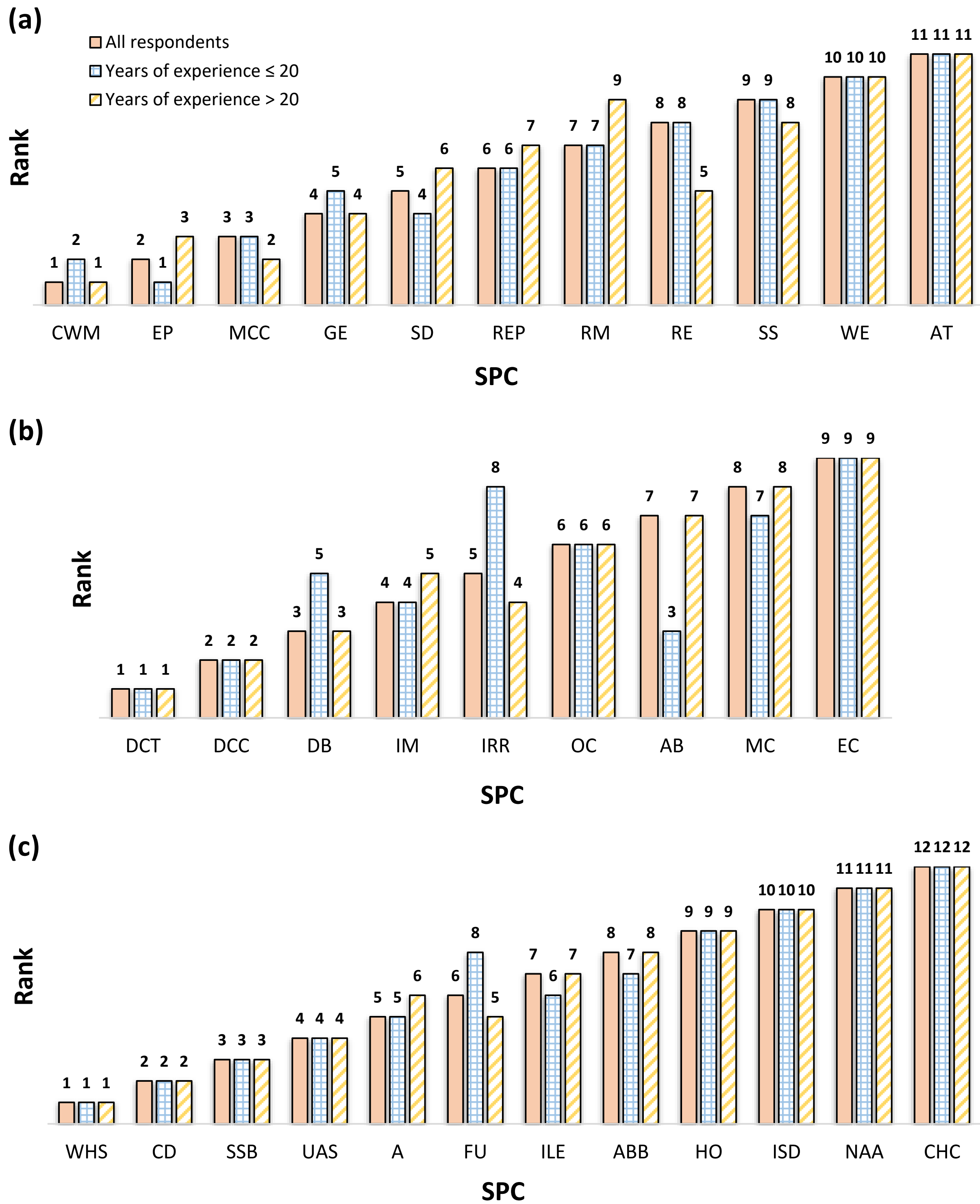

Figure 4.5 Influence of the participants' experience on rank order of (a) Environmental SPCs; (b) Economic SPCs; (c) Social SPCs. Reproduced from Kamali and Hewage (2017b). Used with permission from © Elsevier

years of experience. As demonstrated in Figure 4.5c, all three groups assigned the same ranks to the top ranked SPCs, i.e., WHS, CD, SSB, and UAS. The groups also identically ranked the bottom SPCs, i.e., HO, ISO, NAA, and CHC. This shows the fact that respondents' professional experience does not influence the rating of the top and bottom SPCs. However, there are some discrepancies between SPC rankings in the cases of the middle SPCs. For example, FU was ranked by all respondents as the sixth social SPC, while respondents with less than 20 years of experience and respondents with over 20 years of experience ranked it as the eighth and fifth SPC, respectively.

In the case of the economic category, similarly, unanimity exists between the opinions of the respondents (regardless of their different professional experience) when they ranked DCT and DCC as the top SPCs and also EC as the bottom SPC. Nevertheless, there were minor inconsistencies in the ranks of the middle economic SPCs, in which the two groups with the different experience range dissimilarly prioritized these SPCs (Figure 4.5b).

The environmental category is where less consistency can be seen in terms of SPC ranking by the two respondent groups (Figure 4.5a). While all respondent groups were agreed on the ranks of the bottom SPCs, different rankings were seen in the cases of the top and middle SPCs in the category. However, the rank order changes locally. For example, the CWM SPC was ranked first by all respondents and the group with over 20 years of experience; however, the group with less experience ranked it as the second SPC.

4.5 Summary

Off-site construction has increasingly been used as alternative for conventional construction during the last few years. One of the main methods of off-site construction is modular construction, which offers various advantages that can effectively contribute to sustainable construction. In order to assess and compare the life cycle sustainability performance of modular construction with conventional construction the triple bottom line (TBL) sustainability dimensions, i.e., economic, environmental, and social, should be addressed. The sustainability evaluation criteria (SECs) comprise the TBL sustainability categories i.e., environmental, economic, and social, in which each category includes diverse sustainability performance criteria (SPC) associated with different life cycle phases of a building. Each SPC itself consists of a number of measurable sustainability performance indicators (SPI) by which the SPC can be measured. Moreover, a SPI might include a number of sub-SPIs. There is no published study on sustainability criteria identification for the life cycle performance assessment of residential modular buildings. Thus, in this chapter, the most applicable (important) TBL SPCs were identified, by which the life cycle sustainability performance of residential modular buildings can be evaluated.

Following a comprehensive literature review, 11 environmental SPCs, 9 economic SPCs, and 12 social SPCs were developed. Using these TBL SPCs, a questionnaire survey (Survey A) captured the construction industry practitioners' perceptions of the most applicable sustainability criteria for comparing the sustainability of modular and conventional buildings.

Ranking analysis using the Severity Index (SI) method was the primary technique used for data analysis. Based on each SPC's SI value, it was assigned an importance level according to a severity scale ranging from 'Extremely High' to 'Extremely Low'. Results of analyses showed that among all the 32 TBL SPCs, 15 SPCs were rated as either 'Very High' or 'High' importance criteria (there were no 'Extremely High' importance SPCs) which account for 45% of all SPCs. In addition, 11 SPCs were assigned as 'Medium' importance level, and 6 SPCs were among either 'Low' or 'Very Low' importance level criteria (there were no 'Extremely Low' importance SPCs). This should be mentioned that to ensure the validity of the SPC rankings based on the Severity Index method analyses, the collected data through the survey was analyzed one more time using the ELECTRE 1 MCDA method, which produced the same rank orders for SPCs in all the three sustainability categories.

The top ranked SPCs within the environmental category, 'Construction waste management' and 'Energy performance and efficiency strategies', were the sixth SPC and seventh SPC, respectively, under the overall TBL SPCs. 'Design and construction time' and 'Design and construction costs' in the economic category were highlighted as the top concerns of the respondents. These two SPCs were also significant among all 32 TBL SPCs as they ranked second and third, respectively. Within the social category, 'Construction workforce health and safety' along with 'Community disturbance' were designated as the main concerns. More importantly, the former was rated the top criterion within the overall TBL SPCs as well and the latter was fourth, which indicates the overall sustainability importance of these social SPCs. According to the construction industry practitioners, the economic criteria still play the most significant role in distinguishing the sustainability of two construction methods. Nevertheless, the social dimension of sustainability grabbed more attention compared to the environmental dimension.

The impact of the research participants' professional experience on the rank order of SPCs was examined. In both the economic and the social categories, there were impressive consistencies of SPC rankings assigned by respondents with less than 20 years and over 20 years of professional experience. However, in the case of the environmental SPCs, there were some inconsistencies of the rankings by these two groups of respondents. In addition, the impact of the SPC evaluation criteria on the rank order of SPCs was investigated. The main evaluation criterion of ‘applicability’ was used when analyzing the expert’s feedback to rank the SPCs. However, another analysis was conducted by including both the evaluation criteria of ‘applicability’ and ‘measurability’ with the help of ELECTRE 1 method to rank the SPCs. The results of ELECTRE analyses showed the same overall rankings but locally different rankings for SPCs in all the three sustainability categories. (see Appendix A for details)

The results of this chapter can assist the construction industry experts to gain in-depth understanding of the most significant TBL sustainability criteria when comparing the performance a residential modular building with the performance of similar conventional one. By identification of applicable SPCs, all sustainability dimensions can be analyzed over the life cycle of building projects and different stakeholders’ concerns can be addressed, which can lead to sustainable construction.

Chapter 5 Development of Aggregated Sustainability Indices

A part of this chapter has been published in *Building and Environment* entitled "Life cycle sustainability performance assessment framework for residential modular buildings: Aggregated sustainability indices" (Kamali et al. 2018).

Parts of this chapter will be submitted for possible publication in:

- *Sustainable Cities and Society* entitled "Environmental sustainability benchmarking of modular homes – Part I: Performance quantification" (Kamali et al. 2019a).

- *Journal of Cleaner Production* entitled "Economic sustainability benchmarking of modular homes – Part I: Performance quantification" (Kamali et al. 2019c).

In this chapter, suitable sustainability indicators associated with each selected SPC are determined. In addition, a method to develop sustainability indices for performance evaluation of residential buildings is proposed.

5.1 Background

In the previous chapter, the TBL SPCs have been compiled and ranked within the sustainability categories (i.e., environmental, economic, and social) according to their applicability for sustainability assessment of modular buildings. Those SPCs that were assigned the importance level of either 'Very High', 'High', or 'Medium' by the construction experts have been considered the key sustainability criteria and suitable for life cycle sustainability assessment (LCSA) of residential modular buildings. Therefore, all the SPCs within the environmental and economic categories with the importance level of 'Medium' and higher were selected.

The primary focus of this chapter is on quantification of the selected SPCs (i.e., development of sustainability indices). To this end, in the first part of this chapter, suitable measurable indicators under each SPC were determined. In addition, suitable measurement functions were established to calculate the determined indicators. Subsequently, in the second part of the chapter, the methodology to develop a set of sustainability indices was proposed by which the performance of a given modular building can be evaluated.

5.2 Detailed Methodology

The methodology followed in this chapter comprised different steps as illustrated in Figure 5.1. These steps that lead to development of aggregated sustainability indices have been explained in details as follows.

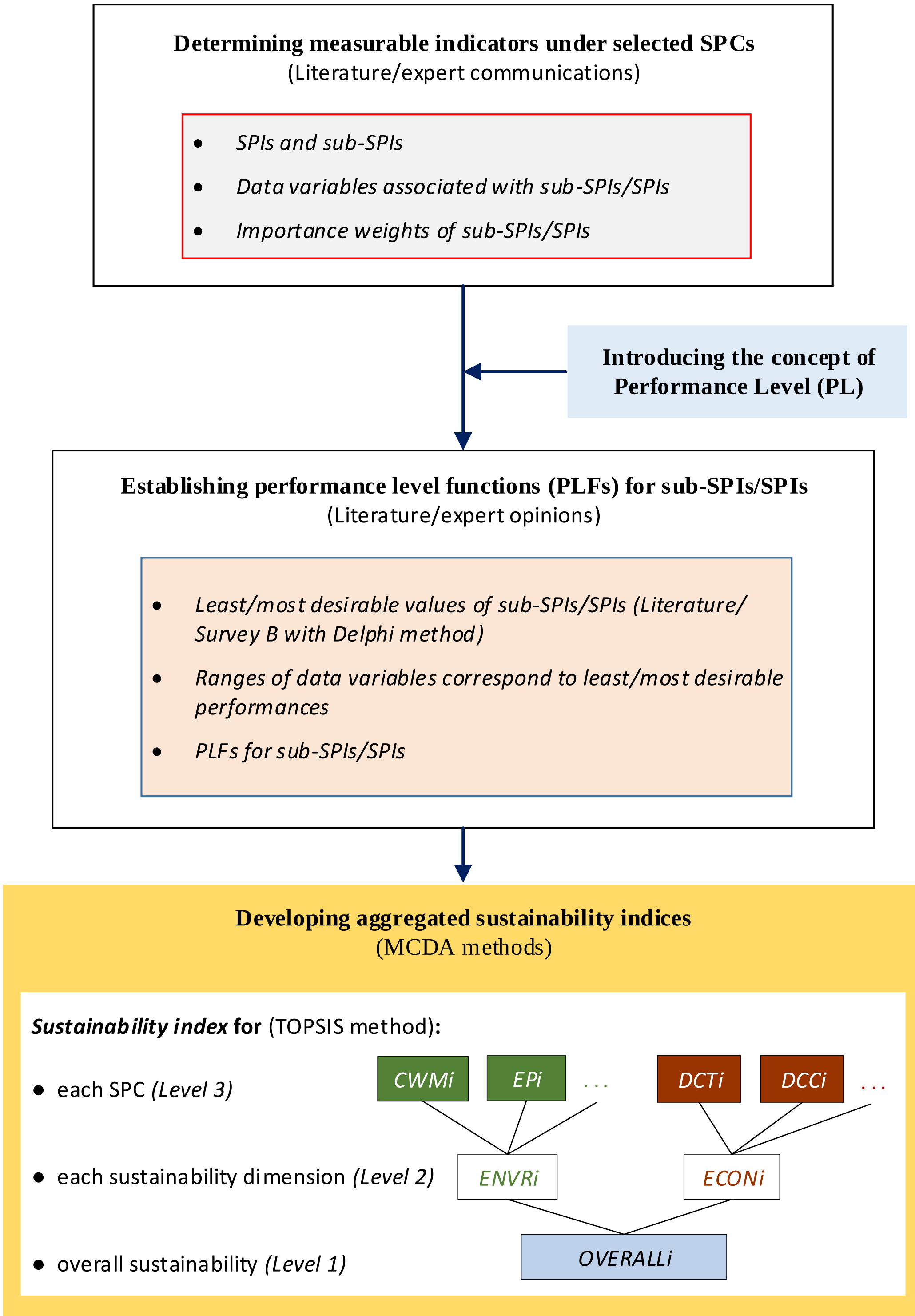

Figure 5.1 Methodology used in Chapter 5

5.2.1 Determination of indicators under SPCs

As stated in Chapter 4, among the 11 SPCs within the environmental category, 8 SPCs were prioritized by the construction practitioners as ‘Medium’ and higher importance criteria and the remaining SPCs received the importance level equal or worse than ‘Low’. In the case of the economic criteria, all the 9 SPCs received the importance level of ‘Medium’ and above. Table 5.1 lists the environmental and economic SPCs with the importance level of ‘Medium’ and up which were selected for sustainability assessment of modular buildings in this research. The table also shows the acronyms of SPCs that were used sometimes in this thesis for simplicity purposes.

Table 5.1 Importance levels of the selected environmental and economic SPCs

Environmental category	Level of Importance	Economic category	Level of Importance
Construction waste management (CWM)	H	Design and construction time (DCT)	VH
Energy performance and efficiency strategies (EP)	H	Design and construction costs (DCC)	VH
Material consumption in construction (MCC)	H	Durability of building (DB)	H
Greenhouse gas emissions (GE)	H	Integrated management (IM)	H
Site disruption and appropriate strategies (SD)	M	Investment and related risks (IRR)	H
Renewable and environmentally preferable products (REP)	M	Operational costs (OC)	H
Regional (local) materials (RM)	M	Adaptability of building (AB)	M
Renewable energy use (RE)	M	Maintenance costs (MC)	M
		End of life costs (EC)	M

As discussed before, each SPC may consist of a number of indicators called sustainability performance indicators (SPIs) in this research. Similarly, a SPI itself can comprise a number of sub-SPIs. Therefore, to measure each selected SPC, relevant SPIs and sub-SPIs should be determined, calculated, and combined. In this step of the methodology, a literature review along with expert consultations were carried out to determine suitable SPIs and sub-SPIs, their required measurement data (i.e., data variables), their performance benchmark values, and also their relative importance weights.

Similar to what has been done for compiling SPCs, the literature regarding rating systems and other published studies were reviewed. Through a few screening processes, all SPIs and sub-SPIs related to a SPC were recognized, listed, renamed, and refined. The approach followed in this research involved choosing simple and easy-to-use measurement methods for the indicators by which each indicator can be calculated by having the minimum amount of data including quantitative and qualitative. Therefore, in cases where the same indicator existed in different references with (different names and) different methods of measurement, the one that provided easiest method and needed less data was selected.

In this study, the determined SPIs associated with a SPC have been denoted by the acronyms of the SPC followed immediately by an integer starting at 1 and ending at *n* (successive integers), where *n* is the total number of SPIs. For example, if the acronyms of a hypothetical SPC is ABC and it comprises two SPIs, these SPIs are denoted by ABC1 and ABC2. Similarly, the same method has been used for symbolizing the sub-SPIs under SPIs with only one difference that the integer denoting the sub-SPI comes after a hyphen. In the same example, if the ABC1 SPI consists of three sub-SPIs, they are denoted by ABC1-1, ABC1-2, and ABC1-3.

5.2.2 Performance Level Functions for Indicators

After determination of suitable indicators (i.e., SPIs and sub-SPIs), their measurement methods were formulated. In this research, a performance level function (PLF) was established for each indicator by which the performance of the subject building with respect to that indicator can be calculated and presented in a dimensionless and normalized way. Depending on the nature of the possible outcomes of a SPI (or sub-SPI), the corresponding PLF can be either a continuous function or a discrete function. In other words, the calculated possible SPI values can be either finite (discrete) or infinite (continuous). For example, if a SPI measures the amount of generated waste during the construction of a building, the possible outcomes can be any real value for the generated waste. Thus, the corresponding PLF will be a continuous function. A continuous PLF itself can be a single function or a piecewise function. On the contrary, if a SPI measures whether a number of specific conditions or items are met in the same project, the possible outcomes cannot be infinite (measurement is based on Yes/No answers). Therefore, the associated PLF will be a discrete step function that is, in fact, a step function is a piecewise function containing all constant "pieces" (Roberts 2018).

Regardless of the form of a PLF (discrete vs continuous), it is important to discuss the unit of its outcomes, i.e., the unit of measurement for the calculated indicator. As stated earlier, the calculated SPIs related to a SPC are combined with their relative importance weights to develop a sustainability index for the SPC. However, the calculated SPIs are not necessarily of the same unit of measurement. For instance, while all the SPIs under the SPC ‘Regional materials (RM)’ are of the same unit (i.e., percentage of regional content), the SPIs under the SPC ‘Construction waste management (CWM)’ are of different units of measurement. Therefore, instead of directly combining SPIs with different units of measurement, first, they should be converted to a common unit and normalized. This is performed automatically by the PLF of each indicator when it calculates the indicator. This research introduced and employed the concept of performance level (PL) as a common unit to enable the calculated indicator to be normalized. PL is a dimensionless unit ranged between 0 and 100. The PL values of 0 and 100 for an indicator are representatives of the least and most desirable performances (i.e., benchmark values) of the indicator, respectively. In other words, a PLF calculates an indicator using the collected data and then transforms the calculated indicator into a PL between 0 and 100.

To develop a PLF for an indicator, its least and most desirable performance values along with the corresponding data variable values should be determined. In this research, the least desirable performance (i.e., $PL = 0$) of an indicator corresponds to the data variable value at which the performance of the subject building with regard to the indicator is considered as the worst in the literature or by experts. For example, the LEED rating system assigns no point for the waste generation rate (WGR) more than 4.0 lb/ft^2. It is possible for a building project to generate more amount of waste; however, the WGR = 4.0 lb/ft^2 is the lower bound threshold equivalent to the least desirable performance ($PL = 0$) of the subject building with regard to the ‘Construction waste diversion’ SPI. Similarly, the most desirable performance ($PL = 100$) is equivalent to the data variable at which the performance of the subject building is considered the best. In the above example, the best performance has been defined as having the WGR of 0.5 lb/ft^2 or less. Therefore, the upper bound waste threshold is set at WGR = 0.5 lb/ft^2 equivalent to the most desirable performance of the subject building with regard to the ‘Construction waste diversion’ SPI ($PL = 100$). In some projects, it might be possible to generate even less waste; however, any WGR less than the 0.5 lb/ft^2 will receive the same $PL = 100$. In other words, in cases where the quantity of the data variable of a SPI (or sub-SPI) lies outside the applicable range (0.5 lb/ft^2 < WGR < 4.0 lb/ft^2 in this example), the performance levels of 0 and 100 are assigned for all performances worse and better than the least and most desirable performances, respectively.

It should be stressed that when searching for the least/most desirable performance values of an indicator and the corresponding data variable thresholds (i.e., data variable boundary conditions), the priority was the sources that reflected regional information. In this regard, because the case study modular buildings assessed in this research were located in the Okanagan, BC, the priority was to use the information specific to this region. For example, if the information about the range of a data variable of a SPI was available for the entire Canada, the entire BC, and the Okanagan, the latter was used in developing the PLF for the SPI.

In the cases of some economic SPCs, such as ‘Design and construction costs’, the least and most desirable performance values of the associated SPIs are sensitive to the construction circumstances in the region in which the subject building in designed and constructed. Therefore, the least/most desirable performances should be obtained locally. For such SPCs (henceforth locality sensitive SPCs), a questionnaire survey (Survey B), was designed based on the Delphi method and implemented to collect this information from the construction firms located in the Okanagan, BC. In general, the Delphi method is a robust technique to reach consensus on problems or questions that cannot be resolved in a single meeting by experts. In this method, a number of experts provide their opinions on an issue through an interactive process (i.e., a few rounds of questioning) until they reach consensus (Stewart 2001). The collected data in the first round (initial opinions) is collated and distributed between the experts again for their review. This process continues until the last round where the consensus is reached by the experts on the answer or solution of the issue (Stitt-Gohdes and Crews 2004; Aigbavboa 2015).

5.2.3 Aggregated Sustainability Indices

As discussed earlier, using a bottom-up approach, this research develops sustainability indices at the following levels:

- Level 3: Sustainability indices for SPCs (e.g., *CWMi*, *EPi*);
- Level 2: Sustainability indices for sustainability dimensions (*ENVRi* and *ECONi*); and
- Level 1: Overall sustainability index (*OVERALLi*).

In the case of Level 3, the sustainability performance indices for SPCs are developed through calculating and combining the associated SPIs. Through a suitable aggregation process (i.e., MCDA methods), the performance levels (PLs) of all the SPIs associated with a SPC, that have been already calculated using the developed PLFs and their weights are aggregated to calculate the sustainability index for the SPC. As for Level 2, once the sustainability indices for SPCs are derived, an index for each of the sustainability dimensions (i.e., environmental and economic) is developed. To this end, similar to the methodology used in Level 3, the sustainability indices of the SPCs associated with a sustainability dimension (e.g., environmental) and their weights are aggregated to develop the sustainability index for the sustainability dimension. Similarly, the overall sustainability index at Level 1 is derived by aggregating the environmental and economic sustainability indices and their weight. The overall sustainability index represents the life cycle performance of the subject building with regard to both the environmental and economic dimensions. As stated before, the social assessment is out of the scope of this research.

In this research, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) MCDA method was used as the aggregation process to develop the sustainability indices at different levels. The TOPSIS method, which is based on the relative closeness to the best performance (i.e., positive-ideal solution, PIS) and relative remoteness from the worst performance (i.e., negative-ideal solution, NIS), provides a more realistic benchmarking approach (Yoon and Hwang 1995). A step-by-step procedure of the TOPSIS method followed in this study has been described in Appendix C.

5.3 Environmental SPCs

In this section, suitable indicators, i.e., SPIs and sub-SPIs, under each environmental SPC were determined and the performance level functions (PLFs) were established. To this end, for each of the eight selected environmental SPCs (Table 5.1), an attempt was made to determine relevant measurable indicators along with their relative importance weights. Then, by determining the performance benchmarks (i.e., the least and most desirable performance values) and the corresponding data variable ranges, the PLFs were established for all the indicators.

Different building codes and standards have been increasing the requirements for environmental performances in recent years. However, according to the literature, meeting these requirements implies a satisfactory environmentally performing building, not necessarily an environmentally sustainable building. Therefore, to attain sustainability, further requirements beyond the minimum requirements should be considered and met during the design and construction phase. As discussed earlier in Chapter 3, rating systems are the most comprehensive sustainability assessment systems whose focus is on the environmental dimension of sustainability. During the literature review to determine suitable indicators under each SPC, it was realized that rating systems are adequately address different aspects of the environmental performance of buildings (i.e., energy, materials, among others) by providing and evaluating relevant indicators. Therefore, in determining suitable SPIs and sub-SPIs under the environmental SPCs, the primary sources included different rating systems such as LEED, BREEAM, and Green Globes, with focus on rating systems tailored for Canadian construction circumstances such as LEED Canada for Homes. The LEED rating system has been distinguished as an excellence source for green building in over 155 countries. Since 2004, over 7600 building projects have applied for LEED certification, which is the second highest number of LEED projects worldwide (CaGBC 2018).

However, in establishing the least/most desirable performance values and the corresponding data variable ranges for the SPIs and sub-SPIs and development of the corresponding PLFs, additional sources such as the governmental and institutional codes and standards, journal articles, among others, have also been reviewed. Moreover, this research benefited from experts' opinions during these processes to gain better understanding and, more importantly, to adjust/tweak the findings to accommodate the construction circumstances in BC, Canada where the case study modular buildings have been located.

Except only one SPC (i.e., 'Material consumption in construction'), this research successfully determined suitable indicators under each environmental SPC and established their corresponding PLFs. In total, 81 indicators have been determined under the environmental SPCs including 37 SPIs and 44 sub-SPIs as summarized in Table 5.2. This table also lists the sources used to identify the measurement method of each indicator and establish the corresponding PLF. Details are provided in the following sections.

Table 5.2 Environmental SPCs and corresponding indicators

SPIs	sub-SPIs	Sources
	Energy performance and efficiency strategies (EP)	
EP1 Envelope insulation	EP1-1 R-value	Lit.., LEED, BCBCC
	EP1-2 Quality of insulation installation	Lit., LEED, RESNET
EP2 Air infiltration		Lit., NRC, LEED
EP3 Windows and glass doors		ENERY STAR, NRC, LEED
EP4 Space heating and cooling equipment	EP4-1 Heating equipment	ENERY STAR, NRC, LEED
	EP4-2 Cooling equipment	ENERY STAR, NRC, LEED
EP5 Heating & cooling distribution system		LEED, EO
EP6 Efficient hot water equipment	EP6-1 Hot water distribution system	LEED, Green Globes
	EP6-2 Pipe insulation	LEED, Green Globes
	EP6-3 Hot water equipment	LEED, Green Globes
EP7 Efficient lighting		ENERGY STAR, LEED
EP8 Efficient appliances		ENERGY STAR, LEED
EP9 Residential refrigerant management		LEED
	Regional materials (RM)	
RM1 Local materials in exterior walls	RM1-1 Framing/wall structure	LBC, LEED, EO
	RM1-2 Siding or masonry	LBC, LEED, EO
RM2 Local materials in floor	RM2-1 Floor framing	LBC, LEED, EO
	RM2-2 Floor flooring	LBC, LEED, EO
RM3 Local materials in foundation		LBC, LEED, EO
RM4 Local materials in interior walls/ceiling	RM4-1 Framing of interior walls	LBC, LEED, EO
	RM4-2 Gypsum board	LBC, LEED, EO
RM5 Local materials in landscape		LBC, LEED, EO
RM6 Local materials in roof	RM6-1 Roof framing	LBC, LEED, EO
	RM6-2 Roof roofing	LBC, LEED, EO
RM7 Local materials in roof, floor, and wall	RM7-1 Cavity insulation	LBC, LEED, EO
	RM7-2 Sheathing	LBC, LEED, EO
RM8 Local materials in other components	RM8-1 Adhesives and sealant	LBC, LEED, EO
	RM8-2 Counters	LBC, LEED, EO
	RM8-3 Doors	LBC, LEED, EO
	Construction waste management (CWM)	
CWM1 Efficient material consumption plans	CWM1-1 Detailed framing plans	Lit., Green Globes, LEED,EO
	CWM1-2 Efficient framing	Lit., Green Globes, LEED,EO
CWM2 Construction waste diversion		Lit., NAHB, Green Globes, LEED, EO
CWM3 Construction waste reuse	CWM3-1 Reuse of façades	Lit., Green Globes, EO
	CWM3-2 Reuse of structural systems	Lit., Green Globes, EO
	CWM3-3 Reuse of non-structural elements	Lit., Green Globes, EO

SPIs	sub-SPIs	Sources
Renewable and environmentally preferable products (REP)		
REP1 Exterior wall content	REP1-1 Framing/wall structure	LEED, EO
	REP1-2 Siding or masonry	LEED, EO
REP2 Floor content	REP2-1 Floor framing	LEED, EO
	REP2-2 Floor flooring	LEED, EO
REP3 Foundation content		LEED, EO
REP4 Interior wall and ceiling content	REP4-1 Framing of interior walls	LEED, EO
	REP4-2 Paints and coatings	LEED, EO
REP5 Landscape content		LEED, EO
REP6 Roof content	REP6-1 Roof framing	LEED, EO
	REP6-2 Roof roofing	LEED, EO
REP7 Roof, floor, and wall content	REP7-1 Cavity insulation	LEED, EO
	REP7-2 Sheathing	LEED, EO
REP8 Other components' content	REP8-1 Cabinets	LEED, EO
	REP8-2 Counters	LEED, EO
	REP8-3 Doors	LEED, EO
Site disruption and appropriate strategies (SD)		
SD1 Construction activity pollution		LEED, EO
SD2 Efficient landscaping	SD2-1 Landscape design	Lit., LEED, EO
	SD2-2 Conventional turf	LEED, EO
	SD2-3 Drought-tolerant plants	LEED, EO
SD3 Heat island effects		Lit., LEED, EO
SD4 Rainwater management	SD4-1 Permeable site	LEED, EO
	SD4-2 Erosion management	LEED, EO
	SD4-3 Roof runoff management	LEED, EO
SD5 Efficient pest control		LEED, EO
Renewable energy use (RE)		
RE1 Renewable electricity		Lit., LEED, NRC, BC Hydro
RE2 Renewable space heating		Lit., NRC
RE3 Renewable water heating		Lit., NRC. LEED
Greenhouse gas emissions (GE)		
GE1 Global warming potential and other impact measures		Lit., ISO, TRACI

Note: Lit. = literature; LEED = Leadership in Energy and Environmental Design; LBC = Living Building Challenge; BREEAM = Building Research Establishment Environmental Assessment Method; NRC = National Research Council Canada; NAHB = National Association of Homebuilders Research Center; ISO = International Organization for Standardization; TRACI = Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts; EO = expert opinions.

5.3.1 Energy Performance and Efficiency Strategies (EP)

Decisions regarding energy performance need to be made early in the design stage to achieve an energy-efficient, cost-effective, and comfortable building (Straube 2017). Currently, energy considerations and minimum performance requirements have been included in many building codes and standards such as the North American codes. This has been initiated many years ago. For example, ASHRAE published one of the first building energy standards, ASHRAE Standard 90.1, in 1975 (Hunn et al. 2010). In Canada, the first national standard for energy performance of buildings (i.e., National Energy Code for Buildings, NECB) was released in 1997. As public awareness and concerns about the negative environmental consequences of the built environment increased, the environmental sustainability considerations in buildings has grown significantly. This led to emerging environmental and energy rating systems. As mentioned above, building codes seek the minimum requirements for energy performance in buildings. This is why green building systems (i.e., rating systems) set stringent performance targets for buildings (Straube 2017). Currently, such systems are grabbing more attention, and have responded to the demand for environmentally sustainable buildings that perform more efficient than buildings that are designed and constructed based on minimum requirements of codes (NAIMA Canada 2018).

Energy performance and efficiency strategies (EP) SPC has been included in almost all of the sources discussed the environmental sustainability of buildings. The intent of this SPC is to investigate and improve the overall energy performance of buildings throughout their use phase. Figure 5.2 shows the determined SPIs and sub-SPIs under this SPC.

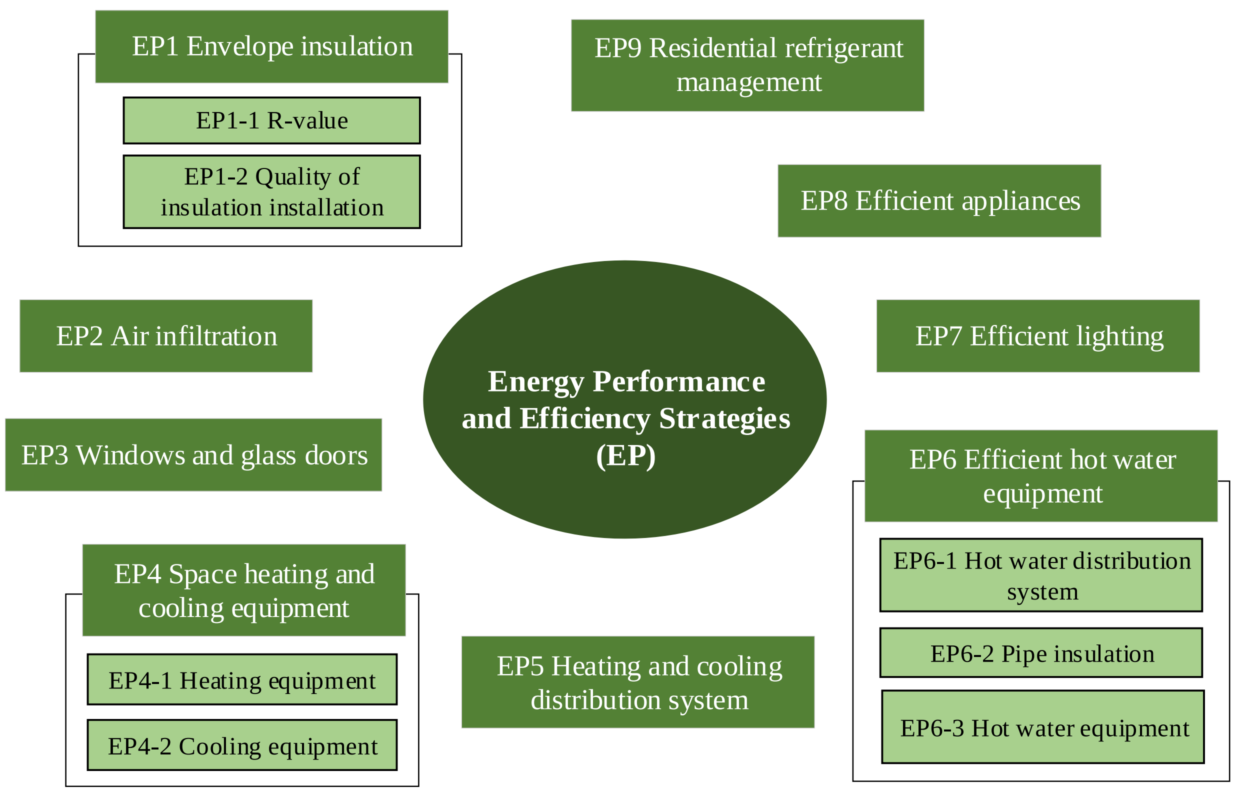

Figure 5.2 SPIs and sub-SPIs associated with ‘Energy performance and efficiency strategies’

5.3.1.1 Envelope insulation (EP1)

Insulation in a building is one of the most significant energy related factors that can efficiently reduce energy consumption and the subsequent costs. The key role of insulation is to save energy by keeping the building warm in winters and cool in summers. Simultaneously, insulation reduces the noise level and provides more comfort to the occupants (NAIMA Canada 2013). In addition, to the literature mentioned that insulation can be considered as the most cost-effective way to lower energy bills. That is, a highly insulated and air-sealed building will require less air conditioning, protecting the owner from potential future costs (NAIMA Canada 2018).

The SPI ‘Envelope insulation (EP1)’ looks for selecting and installing insulation such that the heat transfer and thermal bridging are reduced which results in energy conservation. EP1 consists of two sub-SPIs: ‘EP1-1 R-value’ and ‘EP1-2 Quality of insulation installation’.

R-value (EP1-1)

To define the insulation properties of a building, the term R-value (also called Resistance-value) is used. R-value indicates the resistance level of different materials or assemblies at energy absorption. A material or assembly with higher R-value shows better insulation properties. The insulation properties can also be presented by effective insulation or RSI (R-value Systeme International). Both R-value and RSI measure the materials resistance to the passage of heat; however, they former is presented in imperial system and the latter is the metric equivalent as:

$$R\text{-}value = 5.678 \times RSI \qquad [5.1]$$

This sub-SPI is evaluated based on the amounts of the R-values exceed the minimum values required by the International Energy Conservation Code (IECC) or local codes such as British Columbia Building Code (BCBC), depending on the location of the subject building (i.e., climate zone). The updated version of BCBC requires calculation of the ‘effective’ R-value instead of the ‘nominal’ R-value (BCBCC 2014).

Nominal R-values, which are provided by the manufacturers, are usually different (higher) that the R-values in reality. Therefore, to obtain the actual insulation properties (i.e., thermal resistances) of an assembly, the effective R-values are calculated by including not only insulation, but all individual components such as framing, sheathing, cladding, and so forth.

The minimum effective R-value requirements for the above-ground assemblies of the Okanagan buildings (without heat recovery ventilators, HRVs) including ceilings, walls, and floor are 49.23, 17.49, and 26.52, respectively (BCBCC 2014). These R-values were considered as the lower bound boundary conditions when establishing the PLFs. The adjacent region required higher minimum effective R-value requirements of 59.22, 21.86, and 28.50, respectively that were considered as the upper bound boundary conditions. Therefore, the effective insulation performances of ceilings, walls, and floors, are presented as:

$$PL_{EP1\text{-}1\text{-}ceilings} = 8.01(R - value) - 374.23 \qquad 49.23 \leq R - value \leq 59.22$$
$$PL_{EP1\text{-}1\text{-}walls} = 18.31(R - value) - 300.18 \qquad 17.49 \leq R - value \leq 21.86 \qquad [5.2]$$
$$PL_{EP1\text{-}1\text{-}floor} = 40.40(R - value) - 1051.50 \qquad 26.52 \leq R - value \leq 28.50$$

Consequently, the EP1-1 sub-SPI is calculated using the following PLF:

$$PL_{EP1} = 0.33PL_{EP1\text{-}1\text{-}ceilings} + 0.33PL_{EP1\text{-}1\text{-}walls} + 0.33PL_{EP1\text{-}1\text{-}floor} \qquad [5.3]$$

Quality of insulation installation (EP1-2)

Residential Energy Services Network (RESNET) has published a major revision of the Home Energy Rating System (HERS) standards regarding the quality of insulation in buildings. The installed insulation have been categorized into three grades as follows (RESNET 2013):

Grade I- The best installation that includes almost no gaps or compression. Incomplete fill or compression is allowed up to only 2% of the insulation surface area.

Grade II- The second best installation that allows for up to 2% of missing insulation (gaps) and up to 10% compression over the insulation surface area.

Grade III- The bottom grade in which insulation gaps exceed 2% and compression exceeds 10%. The insulated surface area is considered un-insulated for anything worse than this grade.

As seen above, ‘missing insulation’ and ‘compression and incompletely filled areas’ are the governing parameters when assigning the insulation installation grade. Missing insulation means that there are gaps in the insulation that influence the heat flows through the building envelope and cause more heat losses. The other parameter, compression, is a common issue when using fiberglass batts for insulation since they usually are not cut to the proper size.

Grade 1 provides an energy-efficient insulation in a building. Any sub-par insulation leads to underperforming building with respect to energy consumption (Insulation Institute 2018). Depending on the installed insulation grade described above, the performance level of this sub-SPI is calculated using the PLF below:

$$PL_{EP1\text{-}2} = 10 + 30i \qquad i = 1, 2, 3 \qquad [5.4]$$

Where *i* is 1, 2, or 3 equivalent to Grade III, Grade II, and Grade I, respectively.

The EP1-1 and EP1-2 are of equal importance (CaGBC 2009). Therefore, the following PLF can be used to measure the performance level of the parent SPI:

$$PL_{EP1} = 0.5 \times PL_{EP1\text{-}1} + 0.5 \times PL_{EP1\text{-}2} \qquad [5.5]$$

5.3.1.2 Air infiltration (EP2)

Energy waste due to uncontrolled leakage of air through conditioned spaces should be minimized. Through the EP2 SPI, the amount of air leakage (AL) in the building is calculated and presented in ACH@50PA unit (or equivalent units). The higher the AL value is, the more air leakage in the building. The performance level of a building with respect to air infiltration is determined according to the climate zone that the subject building is located (Straube 2017).

The climate zones have been defined according to Heating Degree Days (HDD) as the average annual temperature. HDD is sum of the degrees of the average daily temperature for all days in a year under 18 °C. Lower HDD values indicate warmer areas. According to Natural Resources Canada, as of February 2015, the following climate zones have been determined for Canada (NRC 2018a):

- Zone 1: HDDs < 3500
- Zone 2: 3500 ≤ HDDs < 6000
- Zone 3: HDDs ≥ 6000

LEED Canada for Homes (CaGBC 2009) provided three different applicable ranges for air leakage in these three climate zones. Lower Mainland (e.g., Vancouver) and a part of the Okanagan, BC (e.g., Kelowna, Penticton) are located in Zone 1. Therefore, the air leakage range applicable in the climate Zone 1 has been used to develop the PLF for this SPI. Consequently, the following PLF can be used to calculate the EP2 performance of the subject building:

$$PL_{EP2} = \begin{cases} -133.34(AL) + 466.69 & 3.0 \leq AL \leq 3.5 \\ -66.66(AL) + 266.65 & 2.5 \leq AL \leq 3.0 \end{cases} \qquad [5.6]$$

where AL is the air leakage of the subject building in ACH@50PA.

5.3.1.3 Windows and glass doors (EP3)

Although windows and glass doors do not consume energy, they are important candidates for heat loss (NRC 2010). Hence, design and installation of high performance windows and glass doors can significantly reduce the energy waste in buildings. The EP3 SPI checks the type of ENERGY STAR certified windows and glass doors designed and installed in a building with respect to the corresponding climate zone. Windows and doors may comply based on either their U-factor (also known as U-value) or energy rating (ER). Higher U-factor values (W/m^2•K) indicate fast heat loss. ER is a dimensionless measure that consists of U-factor, air leakage, and the potential solar gain. Windows and glass doors with higher ER values are more efficient products and can save more energy in buildings (NRC 2010; NRC 2016).As of 2015, the minimum requirements (i.e., minimum ER values and maximum U-factor values) for ENERGY STAR qualified windows and glass doors in different climate zones of Canada were revised and became more stringent (NRC 2010; NRC 2014). Table 5.3 compares the previous and updated minimum requirements for ENERGY STAR qualified windows and glass doors.

Table 5.3 ER and U-factor requirements for windows and glass doors in different zones

Climate Zone	outdated minimum ER (unit-less)	updated minimum ER (unit-less)	outdated maximum U-factor (W/m^2•K)	updated maximum U-factor (W/m^2•K)
1	21	25	1.8	1.6
2	25	29	1.6	1.4
3	29	34	1.4	1.2

Using the thresholds of U-factor or ER in Zone 1, the PLF below was established for this SPI:

$$PL_{EP3} = \begin{cases} -333.35(U-factor)+533.36 & 1.4 \leq U-factor \leq 1.6 \\ -166.65(U-factor)+300 & 1.2 \leq U-factor \leq 1.4 \end{cases} \quad [5.7]$$

$$PL_{EP3} = \begin{cases} 16.67(ER)-416.75 & 25 \leq ER \leq 29 \\ 6.67(ER)-126.75 & 29 \leq ER \leq 34 \end{cases} \quad [5.8]$$

5.3.1.4 Space heating and cooling equipment (EP4)

This SPI intends to minimize the energy consumption due to buildings' heating and cooling systems. The indicator consists of two sub-SPIs: 'EP4-1 Heating equipment' and 'EP4-2 Cooling equipment'. To calculate the performance level of this SPI, the performance level of each sub-SPI is evaluated according to the type of HVAC system for heating and cooling in the building (GBI 2015; CaGBC 2009).

Heating equipment (EP4-1)

The primary heating systems in buildings are:

- Central AC and air source heat pumps (henceforth heat pumps);
- Furnaces;
- Boilers; and
- Ground-source heat pumps

However, according to the experts in this study, ground-source heat systems are seldom installed in buildings in BC; therefore, these systems have not been described in this section.

Heat pumps provide comfort for building occupants by heating the building in winters and cooling it in summers. The heating efficiency of a heat pump is often described by heat seasonal performance factor (HSPF). High efficient heat pumps are those with higher HSPF values. According to Natural Resources Canada, as of 2006, new minimum HSPF requirement of 6.7 was set for heat pumps in Canada (NRC 2004; NRC 2017a). However, rating systems, such as LEED Canada for Homes (CaGBC 2009), require higher values of HSPF as the minimum efficiency requirements, which was used for establishing the PLF for heat pumps in this research. Consequently, if a heat pump was used in a building, the PL of its heating equipment can be calculated as:

$$PL_{EP4\text{-}1} = 125(HSPF) - 1025 \qquad 8.2 \leq HSPF \leq 9.0 \qquad [5.9]$$

Furnaces and boilers only have the capability of heating. The heating efficiency of furnaces (also boilers) are described by annual fuel utilization efficiency (AFUE) that measures the heat a building receives compared to the fuel that the corresponding furnace (or boiler) consumes. For example, a furnace with 75% AFUE, is able to convert 75% of the fuel that it receives (25% of the fuel is lost). The minimum requirement AFUE for furnaces and boilers were determined as 90% and 85%, respectively (CaGBC 2009; NRC 2017b; NRC 2018b). Therefore, in case a furnace is installed as the heating equipment, the PL of this sub-SPI can be calculated as:

$$PL_{EP4\text{-}1} = \begin{cases} 25(AFUE) - 2250 & 90 \leq AFUE \leq 92 \\ 16.667(AFUE) - 1483.3 & 92 \leq AFUE \leq 95 \end{cases} \qquad [5.10]$$

Similarly, if a boiler is installed, the PL of this sub-SPI is calculated as:

$$PL_{EP4\text{-}1} = \begin{cases} 25(AFUE) - 2125 & 85 \leq AFUE \leq 87 \\ 16.667(AFUE) - 1400 & 87 \leq AFUE \leq 90 \end{cases} \qquad [5.11]$$

Cooling equipment (EP4-2)

The central AC, heat pumps, and ground-source heat pumps, have also the capability of cooling. As stated above, furnaces and boilers only have the capability of heating. To measure the cooling performance of an AC or a heat pump, seasonal energy efficiency ratio (SEER) is used. Higher efficient AC and heat pumps are those with higher SEER values. The minimum SEER requirement specified by Natural Resources Canada is 13 (NRC 2004; NRC 2017a); however, the more stringent minimum SEER value of 14 recommended by LEED Canada for Homes (CaGBC 2009) were used to develop the PLF for this sub-SPI as:

$$PL_{EP4\text{-}2} = 50(SEER) - 700 \qquad 14 \leq SEER \leq 16 \qquad [5.12]$$

The performance of a building with respect to the EP4 SPI is measured based on the performance of associated sub-SPIs (i.e., EP4-1 and EP4-2). Depending on the PL values of heating and cooling equipment installed, the performance level of the SPI can be calculated as:

$$PL_{EP4} = 0.5\times PL_{EP4\text{-}1} + 0.5\times PL_{EP4\text{-}2} \qquad [5.13]$$

5.3.1.5 Heating and cooling distribution system (EP5)

This SPI seeks to reduce energy associated with thermal bridges or leaks in buildings' heating and cooling distribution systems. Generally, there are two types of heating and cooling distribution systems: the forced-air systems and the non-ducted HVAC systems (e.g., Hydronic systems). According to the experts in this research, the latter type is not commonly used in residential buildings in BC. Therefore, the PLF for the EP5 SPI was established based on meeting any of the following conditions associated with the forced-air systems (CaGBC 2009):

a - If the tested duct leakage rate ≤ 0.08 cmm (3.0 cfm) at 25 Pascals per 9.2 m^2 (100 ft^2) of conditioned floor area;

b - If the tested duct leakage rate is ≤ 0.03 cmm (1.0 cfm) at 25 Pascals per 9.2 m^2 (100 ft^2) of conditioned floor area;

c - If all ductwork such as the air-handler unit is installed within the conditioned envelope and envelope leakage is minimized;

d - If all ductwork such as the air-handler is visible within conditioned spaces (i.e., no ductwork hidden in chases, floors, walls, ceilings).

Consequently, the PL of the SPI is obtained as:

$$PL_{EP5} = \begin{cases} 0 & none \\ 67 & condition\ a \\ 100 & either\ of\ conditions\ b, c, d \end{cases} \qquad [5.14]$$

5.3.1.6 Efficient hot water equipment (EP6)

The energy consumption due to buildings' hot-water systems can be reduced through design improvement of the hot water system and the layout of the fixtures. This SPI consists of three sub-SPIs: 'EP6-1 Hot water distribution system', 'EP6-2 Pipe insulation', and 'EP6-3 Hot water equipment' (CaGBC 2009; GBI 2015).

Hot water distribution system (EP6-1)

A building shows its best performance with regard to this sub-SPI if either of the following hot water distribution systems is installed (CaGBC 2009):

System 1. Structured plumbing system
System 2. Central manifold distribution system

System 3. Compact design of conventional system

The following PLF can be used to measure the PL of this sub-SPI:

$$PL_{EP6\text{-}1} = \begin{cases} 0 & none \\ 100 & one\ of\ Systems\ 1, 2, 3 \end{cases} \quad [5.15]$$

Pipe insulation (EP6-2)

Insulation of domestic hot water piping can play an important role is reducing energy consumed for heating water. This can be fully obtained by implementing insulation of all hot water piping using international/local standards (e.g., RSI-0.7). To sufficiently insulate the bends, proper insulation of all piping elbows is required. The PL of this sub-SPI can be calculated as:

$$PL_{EP6\text{-}2} = \begin{cases} 0 & no\ insulation\ of\ domestic\ hot\ water\ piping \\ 100 & insulation\ of\ all\ domestic\ hot\ water\ piping \end{cases} \quad [5.16]$$

Hot water equipment (EP6-3)

This sub-SPI checks the availability of a domestic hot water equipment in buildings. In general, there are three types of domestic hot water equipment that are used in residential buildings including gas water heaters, electric water heaters, and drain water heat recovery. However, in the case of each equipment, the performance vary depending on meeting a number of specifications/conditions. Each domestic hot water equipment along with the corresponding PLF is described below.

Gas water heaters. If a gas water heater is installed in the subject building, existence of any of the following conditions is checked:

a- High-efficiency storage water heater: EF ≥ 0.53 (300 liters / 80 gallons)
b- Storage or tank-less water heater: EF ≥ 0.8
c- Combination of water and space heaters: CAE ≥ 0.8

Where EF is the energy factor and CAE is the combined annual efficiency. These measures can be found in the manual of the equipment provided by the manufacturer. Consequently, the function below can be used to calculate the PL of the EP6-3 sub-SPI:

$$PL_{EP6\text{-}3} = \begin{cases} 0 & none \\ 33 & condition\ a \\ 67 & either\ of\ conditions\ b\ and\ c \end{cases} \quad [5.17]$$

Electric water heaters. If this equipment is installed in a building, the performance of the building is measured according to meeting any of the following conditions:

a- High-efficiency storage water heater: EF ≥ 0.89 (300 liters / 80 gallons) b- Tank-less water heater: EF ≥ 0.99

c- Heat pump water heater (ground- or air-sourced): EF ≥ 2.0

Where EF is the energy factor. The following PLF can be used to obtain the PL of EP6-3:

$$PL_{EP6\text{-}3} = \begin{cases} 0 & none \\ 33 & condition\ a \\ 67 & condition\ b \\ 100 & condition\ c \end{cases} \qquad [5.18]$$

Drain water heat recovery. If this equipment is installed, the performance level of the sub-SPI is measured according to meeting the following condition:

a- Heat exchanger that captures waste heat from drain water and pre-heats domestic hot water.

The PLF for EP6-3 was established as:

$$PL_{EP6\text{-}3} = \begin{cases} 0 & none \\ 33 & condition\ a \end{cases} \qquad [5.19]$$

From the PLFs of the three hot water equipment, it can be observed that only the electric water heaters can potentially provide full performance level of 100 (by meeting its c condition).

Once the performance level for each the three sub-SPIs under the EP6 SPI is obtained, the performance of the subject building with respect to this SPI can be measured as:

$$PL_{EP6} = 0.33 \times PL_{EP6\text{-}1} + 0.17 \times PL_{EP6\text{-}2} + 0.5 \times PL_{EP6\text{-}3} \qquad [5.20]$$

5.3.1.7 Efficient lighting (EP7)

Buildings' interior and exterior lighting can consume a large amount of energy if non-efficient equipment is used. The energy performance of a building with respect to this SPI is assessed according to installation of the following lighting equipment (CaGBC 2009):

Interior lighting. Install 5-7 ENERGY STAR labeled light fixtures or ENERGY STAR labeled compact fluorescent light bulbs (CFLs) in high use rooms.

Exterior lighting. All exterior lighting except emergency and lighting required by code for health and safety purposes must have either motion sensor controls or integrated solar electric cells.

Advanced Lighting Package 1. Install ENERGY STAR Advanced Lighting Package using only ENERGY STAR labeled fixtures. The package consists of at least 60% ENERGY STAR qualified hard-wired fixtures and 100% ENERGY STAR qualified ceiling fans (if any).

Advanced Lighting Package 2. Install ENERGY STAR labeled lamps in 80% of the fixtures throughout the home. ENERGY STAR labeled CFLs are acceptable. All ceiling fans must be

ENERGY STAR labeled.

Consequently, the performance level of this SPI is calculated as:

$$PL_{EP7} = \begin{cases} 0 & none \\ 17 & Interior\ lighting \\ 33 & Exterior\ lighting \\ 50 & Both\ interior\ and\ exterior\ lighting\ strategies \\ 100 & thr\ of advanced\ lightaing\ packages\ 1,2 \end{cases} \quad [5.21]$$

5.3.1.8 Efficient appliances (EP8)

Major appliances including refrigerators, dishwashers, and clothes washers, consume a large amount of energy throughout the use phase of buildings. To reduce the energy consumption associated with appliances, this SPI verifies the performance of installed appliances. Use of the following high efficiency appliances can save energy significantly (CaGBC 2009):

a. ENERGY STAR labeled refrigerator(s).

b. ENERGY STAR labeled dishwasher(s) that use 6.0 gallons or less per cycle.

c. ENERGY STAR labeled clothes washer(s).

d- Clothes washer(s) with modified energy factor (MEF) ≥ 2.0 and water factor (WF) < 5.5.

Therefore, the performance of a building with respect to this SPI is calculated as:

$$PL_{EP8} = \begin{cases} 0 & \text{none} \\ 17 & \text{either b, c} \\ 33 & \text{either a, d, bc} \\ 50 & \text{either ab, ac, bd} \\ 67 & \text{either ab, abc} \\ 84 & \text{abd} \\ 100 & \text{a, b, c, d} \end{cases} \quad [5.22]$$

5.3.1.9 Residential refrigerant management (EP9)

This SPI deals with testing air-conditioning refrigerant in order to ensure suitable performance and minimize environmental impacts. A building shows highest performance level if either of the following refrigerant condition is met (CaGBC 2009):

a. Refrigerants are not needed because of passive cooling design.

b. An HVAC system with a non-HCFC refrigerant is installed.

Thus, the performance level function of the EP9 SPI is calculates as:

$$PL_{EP9} = \begin{cases} 0 & none \\ 100 & eithe\ of\ conditions\ a, b \end{cases} \qquad [5.23]$$

5.3.1.10 Relative importance of the SPIs under EP

In this research, the calculated PLs for the SPIs and their weights are aggregated through an aggregation process to develop a sustainability index for the corresponding SPC. The weights of the SPIs can be determined by reviewing different sources in the literature and mainly by focusing on those sources that the SPIs adopted from. In the case of the EP SPC, since all the SPIs are available in both US and Canadian versions of LEED for homes, the corresponding weights were determined by normalization of the maximum scores assigned to each SPI to the total score of all SPIs as listed in Table 5.4 (CaGBC 2009).

Table 5.4 Weight set for the SPIs under the EP SPC

SPI	Weight	SPI	Weight	SPI	Weight
EP1	0.072	EP4	0.143	EP7	0.107
EP2	0.107	EP5	0.107	EP8	0.107
EP3	0.107	EP6	0.214	EP9	0.036
					Sum = 1

5.3.2 Regional Materials (RM)

A building project consists of different assemblies such as foundation, floors, walls, roof, landscape, and so forth. Each assembly itself may include one or more components. For example, exterior walls comprise the framing/wall structure and siding/masonry, among others. Different materials and products have been used to produce each component of a building; therefore, a building is a combination of various materials. Materials and products that are extracted, processed, manufactured, and transported within the same region in which a building is constructed, can positively contribute to the environmental performance of the building from both resource preservation and environmental impacts points of view. For example, a considerable amount of energy is consumed to transport materials and products from the manufacturing centers to the project sites of buildings (CaGBC 2009). Furthermore, the use of regional materials and products can assist with the reduction of construction costs and improvement of the economic impacts.

The SPC 'Regional Materials (RM)' consists of eight SPIs representing different assemblies in a building. In cases where an assembly comprises more than one component, suitable sub-SPIs were developed under that assembly each representing a component. Exception was RM8, where the RM8-1, RM8-2, and RM8-3 were components that did not necessarily belong to a specific assembly. This is why RM8 was named 'Local materials in other components'. Figure 5.3

illustrates the SPIs and sub-SPIs under the RM SPC.

In this research, the local (regional) distance has been defined as 800 km and 2400 km from the project site if materials and products are transported by truck and train, respectively (ILFI 2014; CaGBC 2009).

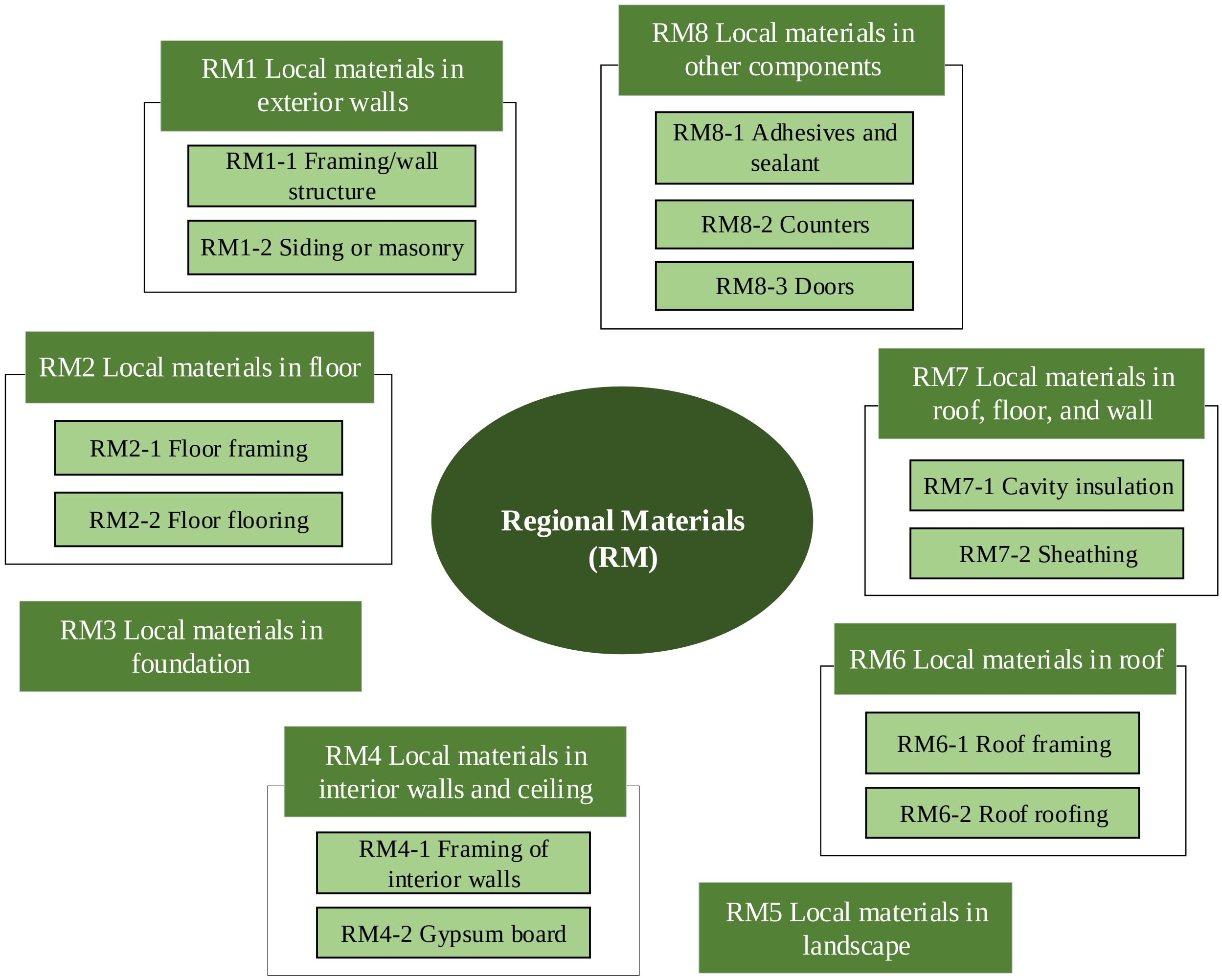

Figure 5.3 SPIs and sub-SPIs related to 'Regional materials'

5.3.2.1 Local materials in exterior wall (RM1)

The RM1 SPI examines whether local materials have been used in the exterior walls assembly of a building. This SPI includes two sub-SPIs: 'RM1-1 Framing/wall structure' and 'RM1-2 Siding or masonry'.

Framing/wall structure (RM1-1)

The performance of the RM1-1 sub-SPI is measured according to the local content of the exterior wall framing/structure (*LWFr*). If the local materials account for 90% and more, the performance level is the best. In other words, if $LWFr$ = 0%, then PL = 0; and if $LWFr$ = 90% and up, then PL = 100. Therefore, the following linear PLF can be used to calculate this sub-SPI:

$$PL_{RM1\text{-}1} = 111.11(LWFr) \qquad 0 \leq LWFr \leq 90\% \qquad [5.24]$$

Siding or masonry (RM1-2)

Similarly, the performance of the second sub-SPI, RM1-2, is in its highest level when the local content of the siding or masonry component of the exterior walls ($LWSi$) accounts for at least 90%. Consequently, the performance of this sub-SPI is calculated using the PLF below:

$$PL_{RM1\text{-}2} = 111.11(LWSi) \qquad 0 \leq LWSi \leq 90\% \qquad [5.25]$$

To calculate the PL of the parent SPI, the PL values of the two sub-SPIs and their weights should be combined. According to LEED Canada for Homes (CaGBC 2009), the relative importance weights of RM1-1 and RM1-2 are equal. Thus, the PL of the RM1 SPI can be calculated as:

$$PL_{RM1} = 0.5 \times PL_{RM1\text{-}1} + 0.5 \times PL_{RM1\text{-}2} \qquad [5.26]$$

5.3.2.2 Local materials in floor (RM2)

The extent to which local materials have been used in a building's floors is investigated using this SPI. The SPI includes sub-SPIs that represent the floor components: 'RM2-1 Floor framing' and 'RM2-2 Floor flooring'.

Floor framing (RM2-1)

The performance of RM2-1 is calculated based on the local material content of the floor framing ($LFFr$). Subsequently, the PLF for this sub-SPI is presented as:

$$PL_{RM2\text{-}1} = 111.11(LFFr) \qquad 0 \leq LFFr \leq 90\% \qquad [5.27]$$

Floor flooring (RM2-2)

The performance of the second sub-SPI under RM2 is measured according to the local content of the flooring component of the building floors ($LFFl$). Therefore, the performance of this sub-SPI is obtained using the following function:

$$PL_{RM2\text{-}2} = 125(LFFl) \qquad 0 \leq LFFl \leq 80\% \qquad [5.28]$$

To measure the PL of the RM2 SPI, the PL values of RM2-1 and RM2-2 and their weights should be aggregated. The weights of RM1-1 and RM1-2 have been specified as 0.333 and 0.667, respectively (CaGBC 2009). Therefore, the PLF for this SPI was established as:

$$PL_{RM2} = 0.333 \times PL_{RM2\text{-}1} + 0.667 \times PL_{RM2\text{-}2} \qquad [5.29]$$

5.3.2.3 Local materials in foundation (RM3)

Foundation is an important assembly of a building, which contains a large amount of materials. According to the literature, the performance level of a building with respect to this SPI is 50 if its foundation contains up to 30% of regional materials. However, the full performance (PL = 100) will occur if this percentage reaches 50% (CaGBC 2009). These boundary conditions were used to develop a piecewise PLF for the RM3 SPI as:

$$PL_{RM3} = \begin{cases} 166.67(LFo) & 0 \leq LFo \leq 30\% \\ 250(LFo) - 25 & 30\% \leq LFo \leq 50\% \end{cases} \qquad [5.30]$$

Where LFo is the local content of foundation.

5.3.2.4 Local materials in interior walls and ceiling (RM4)

This SPI examines what percentage of the materials used in interior walls and ceiling of a building are local. RM4 consists of two sub-SPIs for its components: 'RM4-1 Framing of interior walls' and 'RM4-2 Gypsum board'.

Framing of interior walls (RM4-1)

The performance of this sub-SPI is obtained according to the percentage of local materials used in the framing component of the interior walls ($LIWFr$) as:

$$PL_{RM4\text{-}1} = 111.11(LIWFr) \qquad 0 \leq LIWFr \leq 90\% \qquad [5.31]$$

Gypsum board (RM4-2)

Likewise, RM4-2 measures the performance of the subject building according to the local gypsum board content of the interior walls in the building ($LIWGy$). According to the experts, a building performs excellent if 85% of the gypsum board material used in the interior walls and ceiling have been extracted, processed, and manufactured locally. Thus, the performance of this sub-SPI can be calculated as:

$$PL_{RM4\text{-}2} = 117.65(LIWGy) \qquad 0 \leq LIWGy \leq 85\% \qquad [5.32]$$

The relative importance weights of RM4-1 and RM4-2 came to be equal. Consequently, the following PLF can be used to calculate the PL of the parent SPI:

$$PL_{RM4} = 0.5 \times PL_{RM4\text{-}1} + 0.5 \times PL_{RM4\text{-}2} \qquad [5.33]$$

5.3.2.5 Local materials in landscape (RM5)

This SPI is measured according to the local material content of the landscape (LLa) including deck or patio. A deck is an outdoor platform (flat surface) without a roof often elevated from the ground that usually extends from the building. On the other hand, a patio is a typically paved space located directly on the ground, which can be connected or disconnected from the building.

According to the experts and the literature, the materials used in a building landscape are mostly local. This is in accordance with the strict requirements for the percentage of local materials in landscaping. According to LEED, a percentage of at least 90% is required for local materials of a landscape by which the associated building performs excellent (i.e., if $LLa \geq 90\%$, then PL = 100) (USGBC 2018; CaGBC 2009). However, the consulted experts in this research believed that even a more strict percentage of regional materials is recommended for landscaping in BC. Therefore, the boundary condition of LLa = 95% was used when developing the PLF for this SPI. Consequently, the PL of a building with respect to the RM5 SPI can be presented as:

$$PL_{RM5} = 105.26(LLa) \qquad 0 \leq LLa \leq 95\% \qquad [5.34]$$

5.3.2.6 Local materials in roof (RM6)

The RM6 SPI examines the extent to which the roof assembly materials and products were supplied locally. This SPI includes two sub-SPIs: ‘RM6-1 Roof framing’ and ‘RM6-2 Roof roofing’.

Roof framing (RM6-1)

The performance of RM6-1 is calculated based on the local content percentage in the roof framing ($LRFr$). The best performance occurs when $LRFr$ accounts for 90% or more. Therefore, the following PLF was established for this sub-SPI:

$$PL_{RM6\text{-}1} = 111.11(LRFr) \qquad 0 \leq LRFr \leq 90\% \qquad [5.35]$$

Roof roofing (RM6-2)

According to the literature and expert opinions, the boundary conditions for RM6-2 were determined depending on the local content of the roof roofing ($LRRo$) as: PL = 0 when $LRRo$ = 0%, and PL = 100 when $LRRo$ = 70% and up. Consequently, the performance of RM6-2 can be presented using the following PLF:

$$PL_{RM6\text{-}2} = 142.86(LRRo) \qquad 0 \leq LRRo \leq 70\% \qquad [5.36]$$

The weights of RM6-1 and RM6-2 came to be equal (CaGBC 2009). Therefore, the performance of the corresponding SPI can be calculated as:

$$PL_{RM6} = 0.5 \times PL_{RM6\text{-}1} + 0.5 \times PL_{RM6\text{-}2} \qquad [5.37]$$

5.3.2.7 Local materials in roof, floor, and wall (RM7)

The intent of this SPI is to investigate the local materials used for 'Cavity insulation (RM7-1)' and 'Sheathing (RM7-2)' of a building's walls, roof, and floors. Cavity insulation is employed to reduce the heat loss from buildings surfaces (mainly walls) by filling the air space with materials that prevent or reduce heat transfer. Sheathing is a board or panel as a layer of buildings' different assemblies such as wall, floor, and roof to reinforce them, offer weather resistance, and provide a smooth surface that allows the next layer of materials to apply. Sheathing can be made from different materials such as gypsum, engineered timber, plywood, and so forth.

Cavity insulation (RM7-1)

The performance of a building with respect to RM7-1 is calculated based on the local content of the cavity insulation (not rigid foam insulation) ($LCIn$) of roof, floor, and walls. The boundary conditions are: PL = 0 and PL = 100 when $LCIn$ = 0% and $LCIn$ = 20%, respectively. Therefore, the PLF for this sub-SPI was established as:

$$PL_{RM7\text{-}1} = 500(LCIn) \qquad 0 \leq LCIn \leq 20\% \qquad [5.38]$$

Sheathing (RM7-2)

Similarly, the performance of a building with respect to RM7-2 is measured based on the local content of the floor, roof, and wall's sheathing (LSh). The boundary conditions are: PL = 0 when LSh = 0%, and PL = 100 when LSh = 65% and up. Therefore, the following PLF was established for this sub-SPI:

$$PL_{RM7\text{-}2} = 153.85(LSh) \qquad 0 \leq LSh \leq 65\% \qquad [5.39]$$

When the PL values of RM7-1 and RM7-2 are obtained, the PL of the corresponding RM7 SPI can be calculated as:

$$PL_{RM7} = 0.5 \times PL_{RM7\text{-}1} + 0.5 \times PL_{RM7\text{-}2} \qquad [5.40]$$

5.3.2.8 Local materials in other components (RM8)

The RM8 SPI evaluates the regional material content in other important components of a building that have not been addressed in the previous SPIs and sub-SPIs. This SPI comprises three sub-SPIs: 'RM8-1 Adhesives and sealant', 'RM8-2 Counters', and 'RM8-3 Doors'.

Adhesives and sealant (RM8-1)

The PL of RM8-1 is measured based on the local content of adhesives and sealant in a building (LAd). Based on the expert opinions, the boundary conditions specified to score this indicator were tweaked to suit buildings constructed in BC as PL = 0 if LAd = 0%; and PL = 100 if LAd =

40% and up. Hence, the following PLF was established to evaluate this sub-SPI:

$$PL_{RM8\text{-}1} = 250(LAd) \qquad 0 \leq LAd \leq 40\% \qquad [5.41]$$

Counters (RM8-2)

Likewise, the boundary conditions for evaluation of the local material content of the building's counters (LCo) including kitchens and bathrooms were revised according to the construction circumstances in BC. Consequently, the PLF below was established to measure RM8-2:

$$PL_{RM8\text{-}2} = 125(LCo) \qquad 0 \leq LCo \leq 80\% \qquad [5.42]$$

Doors (RM8-3)

The PL of this indicator is measured based on the local content of the building doors and trims (LDo), excluding garage or insulated doors as (CaGBC 2009):

$$PL_{RM8\text{-}3} = 111.11(LDo) \qquad 0 \leq LDo \leq 90\% \qquad [5.43]$$

By having the calculated PLs and weights of the three sub-SPIs, the corresponding SPI can be calculated. The weights of all sub-SPIs have been reported equal in the literature and this was confirmed by the experts in this research (CaGBC 2009). Therefore, the PL of RM8 can be measured as:

$$PL_{RM8} = 0.333 \times PL_{RM8\text{-}1} + 0.333 \times PL_{RM8\text{-}2} + 0.333 \times PL_{RM8\text{-}3} \qquad [5.44]$$

5.3.2.9 Relative importance of the SPIs under RM

As stated before, the calculated performance levels of the determined SPIs and their relative importance weights are aggregated through an aggregation process to develop the sustainability indices for the corresponding SPCs. The weights of the above-discussed SPIs under the RM SPC were determined using the literature with the focus on the sources that the SPIs adopted from as listed in Table 5.5.

Table 5.5 Weight set for the SPIs under the RM SPC

SPI	Weight	SPI	Weight	SPI	Weight
RM1	0.118	RM4	0.118	RM7	0.118
RM2	0.176	RM5	0.058	RM8	0.176
RM3	0.118	RM6	0.118		
					Sum = 1

5.3.3 Construction Waste Management (CWM)

Construction is not an environmentally responsible activity and the generated waste results in negative environmental impacts (Boiral and Henri 2012; Lu and Tam 2013; Coelho and de Brito

2012). Construction and demolition waste (C&D) is defined as the waste generated during the construction, renovation, and demolition of a building (Kofoworola and Gheewala 2009). C&D waste consists of damaged or surplus materials and products during construction activities. In addition, all temporarily materials and products that are used on or off the project final location or during the transportation of modules from the factory to the final project site are considered as C&D waste (Roche and Hegarty 2006). The waste generated in the use phase of a building is mostly municipal waste (except the waste due to renovation, maintenance, and repair); therefore, the C&D waste and its management is mainly related to the design and construction phase and the end of life phase.

The SPC 'Construction waste management (CWM)' is a significant criterion in performance evaluation of building projects. The findings in the previous chapter showed that, this SPC was considered the top concerns of the construction practitioners when comparing the performance of on-site construction and off-site construction (see Table 4.4 in Chapter 4). The CWM SPC evaluates a building's performance with respect to implementation of the 'reduce', reuse', and 'recycle' strategies (also known as 3Rs) as the most construction waste management priorities as shown in Figure 5.4 (Wang et al. 2010). In other words, the intent of this SPC is to investigate if during the life cycle of a building, strategies such as reducing the waste generation, reusing the products or components in other building projects, and recycling have been performed. However, since the recycling strategy has been addressed under the 'Renewable and environmentally preferable products (REP)' SPC, this strategy was not repeated under CWM to avoid double counting. In addition to 3Rs, there are two more waste management strategies including 'recover or incinerate' and 'landfill or dispose'. These strategies are the least preferable strategies (Figure 5.4); therefore, were not discussed under the CWM SPC in this research.

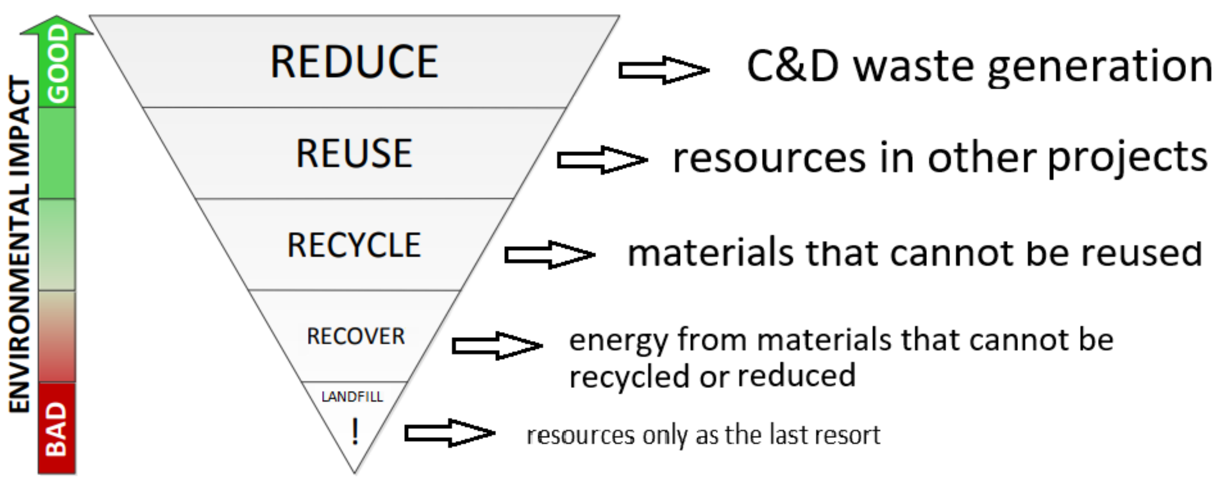

Figure 5.4 Construction waste management hierarchy

In determining suitable indicators under the CWM SPC, a total of three SPIs: ‘CWM1 Efficient material consumption plans’, ‘CWM2 Construction waste diversion’, and ‘CWM3 Construction waste reuse’ were determined among which two SPIs comprised a number of sub-SPIs as illustrated in Figure 5.5. CWM1 and CWM2 address the waste management related to the design and construction phase, while CWM3 addresses the waste management at the end of life phase.

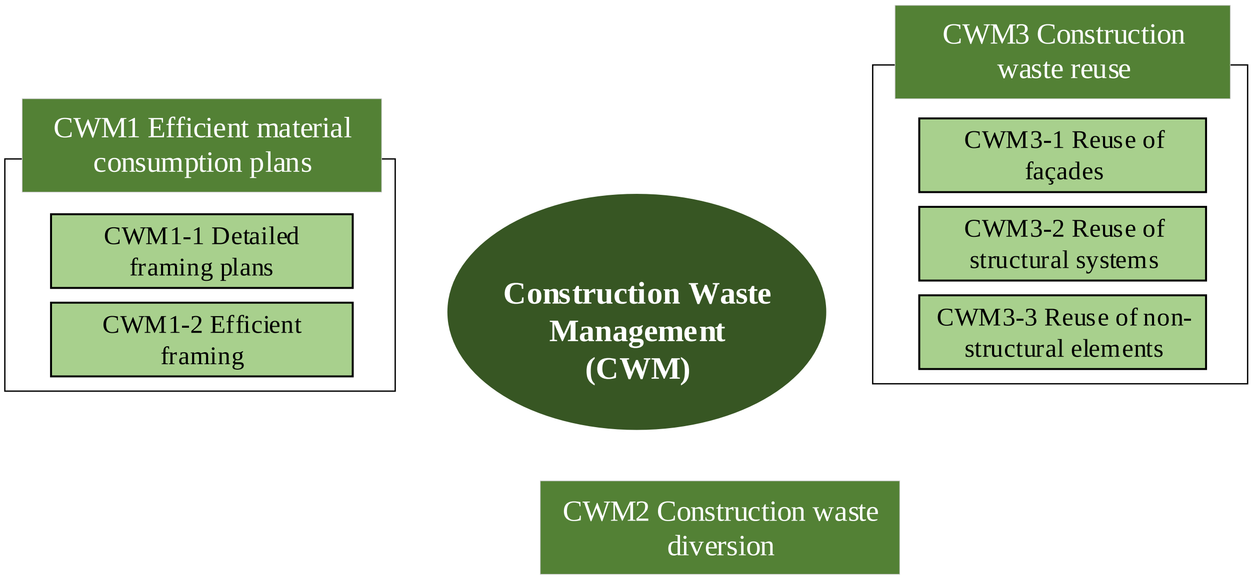

Figure 5.5 SPIs and sub-SPIs associated with ‘Construction waste management’

5.3.3.1 Efficient material consumption plans (CWM1)

The CWM1 SPI considers the reduce strategy in the design stage of the life cycle’s design and construction phase. Many studies emphasized that the ‘reduce’ strategy is the most effective factor in the process of waste management for reduction of waste disposal and the associated environmental burdens (Esin and Cosgun 2007; Wang et al. 2010; Peng et al. 1997). The main advantages of the reduce strategy are: (a) generating less waste; and (b) avoiding the costs of waste recycling and waste transportation and disposal (Poon 2007). Considerations of suitable plans earlier in the design stage will limit the consumption of unnecessary construction materials in the construction stage that helps to increase resource conservation and the subsequent environmental and economic performances. This SPI consists of two sub-SPIs: ‘CWM1-1 Detailed framing plans’ and ‘CWM1-2 Efficient framing’.

Detailed framing plans (CWM1-1)

Detailed framing explains the minimum material requirements for construction of different components in a building; hence, it can save a considerable amount of resources during construction. To measure the performance of a building with regard to this sub-SPI, the following measures are evaluated (GBI 2015; CaGBC 2009):

a- In the design stage, detailed framing documents including the plans and the work scope is available. The documents should include all the details for use on the building project site such as the precise locations of all framing members in different assemblies (e.g., walls, floors, and roof) along with their spacing and sizes.

b- If measure ‘a’ is implemented, then existence of detailed cut list and also the lumber order documents associated with the framing plans and/or the work scopes (measure ‘a’) is checked.

Depending on meeting the above measures, the PL of this sub-SPI is obtained by the PLF below:

$$PL_{CWM1\text{-}1} = \begin{cases} 0 & none \\ 50 & a \\ 100 & both\ a\ and\ b \end{cases} \qquad [5.45]$$

Efficient framing (CWM1-2)

Efficient framing can lead to less material consumption; therefore, it can effectively contribute to less waste generation. This sub-SPI investigates whether the efficient framing items have been implemented during the construction stage o buildings. As seen in Table 5.6, the efficient framing items were categorized into two groups, G1 and G2. Implementation of an item from the G1 group has more contribution to waste reduction when compared to implementation of an item from the G2 group. The performance of a given building with respect to this sub-SPI can be determined by checking the implemented items under G1 and G2.

Table 5.6 Efficient framing items

G1	G2
Precut framing packages	Joist spacing in ceiling ≥ 16” (40 cm) oc
Open-web floor trusses	Finger-jointed framing materials
Structural insulated panel (SIP) walls	Joist spacing in floors ≥ 16” (40 cm) oc
Structural insulated panel (SIP) roof	Joist spacing in roof ≥ 16” (40 cm) oc
Structural insulated panel (SIP) floors Stud spacing ≥ 16” (40 cm) oc	Implement any two of the following: - size headers for actual loads - ladder blocking/drywall clips - two-stud corners
Note. oc = on center	

Therefore, the PLF below can be used to calculate the performance level of CWM1-2:

$$PL_{CWM1\text{-}2} = Min\{33.3i + 16.7j, 100\} \quad i = 1, 2, \ldots, 6 \text{ and } j = 0, 1, 2, \ldots, 5 \qquad [5.46]$$

Where i and j are the number items under G1 and G2, respectively, which have been incorporated in the design of the subject building.

To calculate the PL of the CWM1 SPI, the calculated PLs of the two sub-SPIs and their weights are aggregated. According to LEED Canada for Homes (CaGBC 2009), the relative importance weights of CWM1-1 and CWM1-2 came to be 0.4 and 0.6, respectively. Therefore, the following PLF was established to measure the CWM1 SPI:

$$PL_{CWM1} = 0.4 \times PL_{CWM1\text{-}1} + 0.6 \times PL_{CWM1\text{-}2} \qquad [5.47]$$

5.3.3.2 Construction waste diversion (CWM2)

This SPI also addresses the 'reduce' strategy of CWM. Although suitable 'reduce' factors might have been incorporated into the design of a building, the actual waste generated during the construction stage should be investigated. Waste generation rate (WGR) is a common measure to evaluate waste management in the construction stage (Bakshan et al. 2015). WGR is calculated by dividing the total weight of the generated waste during construction by the total floor area of the building (Wang et al. 2019; Formoso et al. 2002).

Different methods have been used to collect the data of waste in construction projects including direct observation (Poon et al. 2001), surveys (Treloar et al. 2003; McGregor et al. 1993; Tam et al. 2007), collecting data of waste loads transported by trucks (Poon et al. 2004), contractors' waste records (Skoyles 1976), and on-site sorting and weighing the generated waste (Bossink and Brouwer 1996). In terms of waste classification method, some studies classified the generated waste into different categories (e.g., Treloar et al. 2003; Bossink and Brouwers 1996), while other studies viewed the generated waste as a single category (e.g., Poon et al. 2004). In this research, the latter approach has been used when calculating WGR.

The CWM2 SPI seeks reduction of waste generated during the construction of a building (BRE 2016; CaGBC 2009; GBI 2015) to a level below the construction industry average. The average waste generated by new construction is 3.9 lb per 1 ft^2 of the building floor area (19 $kg/1m^2$) (Merlino 2011; Monroe 2008; CaGBC 2009). The SPI is measured using the WGR data variable. Since waste is a cost criterion (as opposed to benefit), the PLF for this SPI is expected to be a monotonically decreasing function that means the more construction waste is generated, the worse performance level is assigned. The average construction waste of 3.9 lb/ft^2 was rounded up to 4.0 lb/ft^2 as the lower bound boundary condition corresponding to the least desirable performance (PL = 0). Different minimum (i.e., optimum) values for construction waste have been reported in different studies. However, the most rigorous amount was 0.5 lb/ft^2 (CaGBC 2009) that was chosen as the upper bound boundary condition (PL = 100). Consequently, the following PLF to calculate the PL this SPI was established:

$$PL_{CWM2} = \begin{cases} -16.68\ (WGR) + 66.67 & 3.0 \leq WGR \leq 4.0 \\ -33.33\ (WGR) + 116.67 & 0.5 \leq WGR \leq 3.0 \end{cases} \quad [5.48]$$

If WGR in a building project came to be any amount more than 4.0 lb/ft^2, the same PL = 0 is assigned. Likewise, the PL = 100 is assigned for all outstanding WGR under 0.5 lb/ft^2.

5.3.3.3 Construction waste reuse (CWM3)

The intent of this SPI is to investigate the construction waste management at the end of the building lifetime. Implementation of 'reuse' strategy can prolong the life cycle of existing buildings, reduce resource consumption and also waste, maintain cultural resources, and decrease the environmental burdens due to new building projects. Nevertheless, according to the literature and expert views, this strategy is not appropriately incorporated into the design and implemented in the construction of buildings in today's construction industry since there is no systematic supply chain for reused components (structural and non-structural). However, on rare occasions, some parts of the existing old buildings are reused in new projects.

To identify which parts and components of a new building (i.e., subject building) will be used again in another building project, it is required to wait until the end of the building's lifetime (e.g., 50 or 60 years) which is not possible. To have an estimate, it can be assumed that the amount of parts and components that are taken from existing old buildings at the end of their life and reused in a new building is the same as the amount of reused parts and components of this building at the end of its life in new projects. This is not a faultless assumption because the old buildings which are now at the end of their lifetime have been designed and constructed many years ago which cannot be in accordance with today's new designs and technologies in terms of reusable parts and components. However, this assumption, at least, can provide an idea of the 'reuse' capability of a building in practice. In the case of modular buildings, even this imperfect assumption is not applicable. As known, modular construction has been evolved in the last few decades. Consequently, approximately no modular buildings have reached the end of life to observe if any parts or components are reused in new modular buildings. This was confirmed with the data provided by the modular homebuilders for the case study modular projects in this research where none of the modular case study buildings benefited from reused components or elements. Thus, the CWM3 SPI was eliminated and the CWM SPC is calculated based on only CWM1 and CWM2 SPIs. However, the determined sub-SPIs under the CWM3 SPI and the corresponding PLFs have been provided in Appendix D.

5.3.3.4 Relative importance of the SPIs under CWM

To calculate the sustainability index for CWM, the PLs of the associated SPIs and their relative importance weights should be combined. It should be noted that the ideas for measurement of CWM1 and CWM2 were borrowed from LEED (CaGBC 2009; USGBC 2018). Likewise, the initial measurement method for CWM3 was adopted from Green Globes for multi-family buildings (GBI 2015; GBI 2014). However, this SPI was not included as one of the SPIs under CWM. Therefore, the weights of CWM1 and CWM2 came to be 0.625 and 0.375, respectively.

5.3.4 Renewable and Environmentally Preferable Products (REP)

Renewable and environmentally preferable products are products that are built using materials that have less environmental impacts. For example, virgin materials that have already been extracted, processed, and used in a product, can be recycled (i.e., renewed) and used again in a new product or project. Another example is to use certified lumbar in the construction of a building. The use of environmentally responsible materials in different products and components of a building can significantly reduce the demand for raw materials, which can result in enormous resource conservation. This can also mitigate the negative environmental impacts due to reduction in the energy required to extract and process new materials even though the preparation of the used materials to be recycled or reused requires energy (BRE 2016).

The ‘Renewable and environmentally preferable products (REP)’ SPC examines the use of environmentally friendly materials in buildings and includes eight SPIs as shown in Figure 5.6.

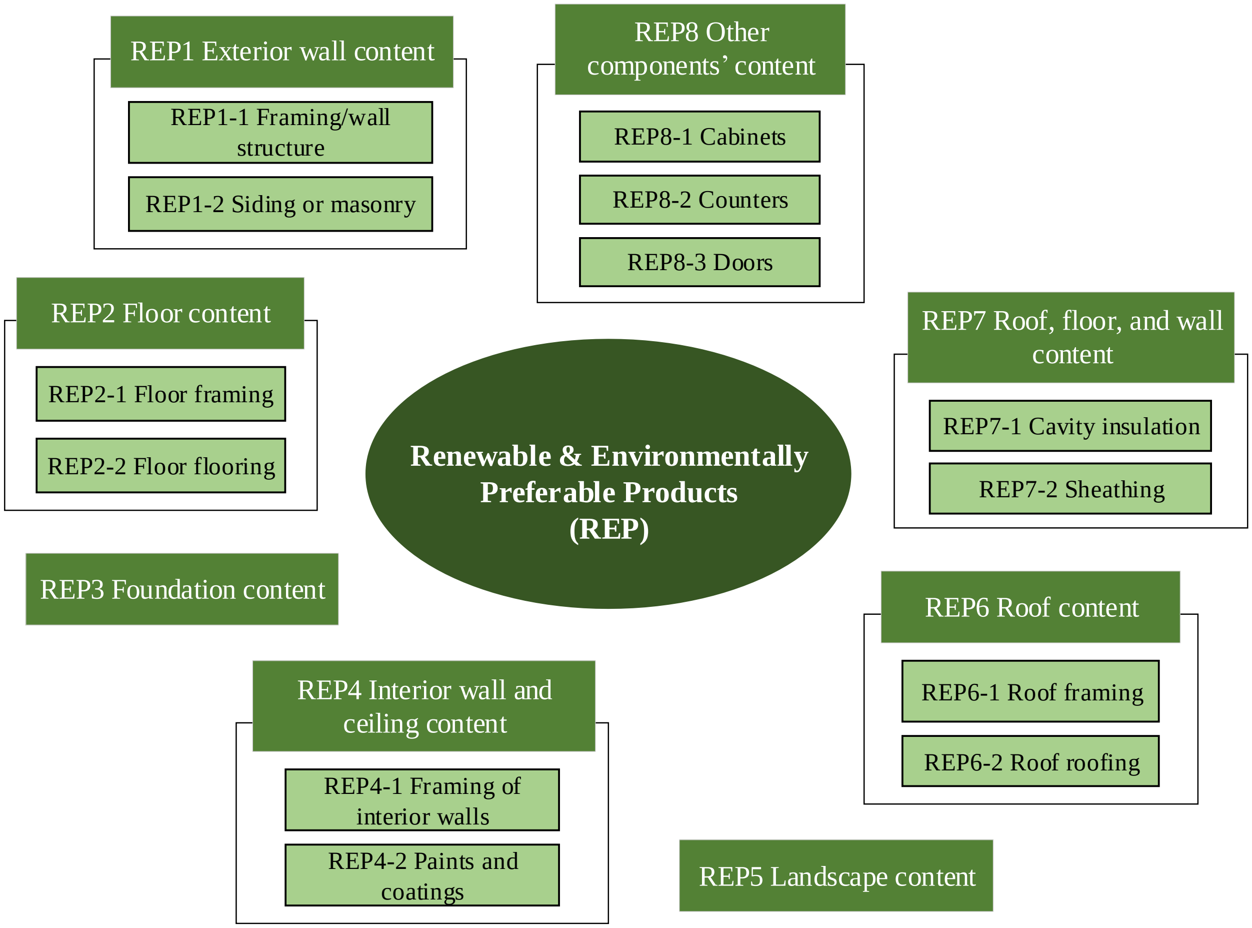

Figure 5.6 SPIs and sub-SPIs under 'Renewable and environmentally preferable products'

This SPC comprises eight SPIs representing different assemblies in a building. In addition, some SPIs include two or three sub-SPIs to address different components correspond to an assembly.

5.3.4.1 Exterior wall content (REP1)

The REP1 SPI examines to what extent environmentally friendly materials have been used in the exterior walls assembly of a building. REP1 comprises two sub-SPIs: 'REP1-1 Framing/wall structure' and 'REP1-2 Siding or masonry'.

Framing/wall structure (REP1-1)

This sub-SPI investigates the percentage of FSC-certified or reclaimed materials, or finger joint studs used in the exterior wall framing/structure (WFr). The boundary conditions for this sub-SPI were determined based on the recommended values in the literature and also expert opinions as PL = 0 and 100 if WFr = 0% and 80%, respectively. Consequently, the performance of REP1-1 is presented as:

$$PL_{REP1\text{-}1} = 125(WFr) \qquad 0 \leq WFr \leq 80\% \qquad [5.49]$$

Siding or masonry (REP1-2)

Likewise, the performance level of REP1-2 is 100 when the recycled, reclaimed, or FSC-certified materials used in the siding or masonry component of the exterior walls (WSi) accounts for 70% and up. Thus, the PL of this sub-SPI is obtained by means of the following function:

$$PL_{REP1\text{-}2} = 142.85(WSi) \qquad 0 \leq WSi \leq 70\% \qquad [5.50]$$

To calculate the PL of the parent SPI, the PLs of the associated sub-SPIs should be calculated and combined with their relative importance weights. The weights of REP1-1 and REP1-2 came to be equal (CaGBC 2009); therefore, the performance of REP1 can be calculated as:

$$PL_{REP1} = 0.5 \times PL_{REP1\text{-}1} + 0.5 \times PL_{REP1\text{-}2} \qquad [5.51]$$

5.3.4.2 Floor content (REP2)

The amount of environmentally responsible materials consumed in the construction of floors is evaluated by this SPI. The SPI includes two sub-SPIs: ‘REP2-1 Floor framing’ and ‘REP2-2 Floor flooring’ that address two components of the floor assembly.

Floor framing (REP2-1)

The performance of REP2-1 is calculated based on the extent to which the FSC-certified or reclaimed materials have been used in the floor framing (FFr). According to the experts, the upper boundary for the percentage of FFr, which corresponds to PL = 100, was set at 70%. Therefore, the PLF for this sub-SPI was presented as:

$$PL_{REP2\text{-}1} = 142.86(FFr) \qquad 0 \leq FFr \leq 70\% \qquad [5.52]$$

Floor flooring (REP2-2)

The performance of the second sub-SPI under REP2 is measured according to the percentage of the floor’s flooring that contains environmentally responsible materials (FFl) such as cork, linoleum FSC-certified or reclaimed wood, bamboo, sealed concrete, recycled materials, or any combination of them. The boundary conditions were set similar to the previous sub-SPI. Consequently, the performance of this sub-SPI is obtained using the following PLF:

$$PL_{REP2\text{-}2} = 142.86(FFl) \qquad 0 \leq FFl \leq 70\% \qquad [5.53]$$

In addition, the weights of REP2-1 and REP2-2 have been specified as 0.333 and 0.667, respectively (CaGBC 2009). Hence, the performance of REP2 can be calculated as:

$$PL_{REP2} = 0.333 \times PL_{REP2\text{-}1} + 0.667 \times PL_{REP2\text{-}2} \qquad [5.54]$$

5.3.4.3 Foundation content (REP3)

This SPI focuses on the content of a building foundation. The data variable to calculate the performance level of this SPI is Fo which indicates what percentage of the foundation content is supplemental cementious materials. According to the literature, the foundation performs moderately (PL = 50) if it contains 30% of supplemental cementious materials. However, its performance reaches PL = 100 when it increases to 50% (CaGBC 2009). These boundary conditions were used to develop a piecewise PLF for the SPI as:

$$PL_{REP3} = \begin{cases} 166.67(Fo) & 0 \leq Fo \leq 30\% \\ 250(Fo) - 25 & 30\% \leq Fo \leq 50\% \end{cases} \qquad [5.55]$$

5.3.4.4 Interior wall and ceiling content (REP4)

The REP4 SPI evaluates the performance of the subject building with regard to REP content of its interior walls and ceiling. The SPI consists of two sub-SPIs including ‘REP4-1 Framing of interior walls’ and ‘REP4-2 Paints and coatings’.

Framing of interior walls (REP4-1)

The performance of the first sub-SPI is obtained according to the percentage of FSC-certified or reclaimed materials used in the framing component of the interior walls ($IWFr$) as:

$$PL_{REP4\text{-}1} = 125(IWFr) \qquad 0 \leq IWFr \leq 80\% \qquad [5.56]$$

Paints and coatings (REP4-2)

The performance of the second sub-SPI is evaluated based on the extent to which recycled paint that satisfies Green Seal standard (i.e., GS-43) or any other standard is used in painting and coating of the interior walls and ceiling ($IWPa$). By applying the boundary conditions for the $IWPa$ data variable, the following PLF was established to calculate this sub-SPI:

$$PL_{REP4\text{-}2} = 111.11(IWPa) \qquad 0 \leq IWPa \leq 90\% \qquad [5.57]$$

Furthermore, the relative importance weights of the two sub-SPIs came to be equal (CaGBC 2009). Consequently, the performance level of the corresponding SPI can be calculated as:

$$PL_{REP4} = 0.5 \times PL_{REP4\text{-}1} + 0.5 \times PL_{REP4\text{-}2} \qquad [5.58]$$

5.3.4.5 Landscape content (REP5)

The performance of REP5 is measured according to the amount of recycled, FSC-certified or reclaimed content in the building’s landscape including the deck or patio (La). While the literature requires high percentages of the environmentally friendly materials at which the building presents its best performance (i.e., up to La = 90%); the experts in this research believed that even La = 70% can be considered as the best performance for this SPI in British Columbia. Hence, the performance level of the subject building with respect to REP5 can be calculated using the PLF below:

$$PL_{REP5} = 142.86(La) \qquad 0 \leq La \leq 70\% \qquad [5.59]$$

5.3.4.6 Roof content (REP6)

This SPI examines the amount of the roof content that were supplied by REP materials. REP6 consists of two sub-SPIs including ‘REP6-1 Roof framing’ and ‘REP6-2 Roof roofing’.

Roof framing (REP6-1)

The performance of this sub-SPI is calculated based on the FSC-certified content of the roof framing (RFr). The least and most desirable performances take place when the RFr percentage in the roof structure reaches 0% and 60%, respectively. Therefore, the PLF presented below can be used to calculate REP6-1:

$$PL_{REP6\text{-}1} = 250(RFr) \qquad 0 \leq RFr \leq 40\% \qquad [5.60]$$

Roof roofing (REP6-2)

According to the literature and expert opinions, the boundary conditions for REP6-2 were determined based on the recycled content of the roof roofing (RRo) as PL = 0 when RRo = 0% and PL = 100 when RRo = 75%. Therefore, the PL of this sub-SPI is calculated as:

$$PL_{REP6\text{-}2} = 133.33(RRo) \qquad 0 \leq RRo \leq 75\% \qquad [5.61]$$

The weights of REP6-1 and REP6-2 came to be equal (CaGBC 2009). Thus, the performance level of the corresponding SPI is obtained using the PLF below:

$$PL_{REP6} = 0.5 \times PL_{REP6\text{-}1} + 0.5 \times PL_{REP6\text{-}2} \qquad [5.62]$$

5.3.4.7 Roof, floor, and wall content (REP7)

This SPI investigates the use of environmentally responsible materials when performing cavity insulation and sheathing of the roof, floor, and wall assemblies.

Cavity insulation (REP7-1)

The performance of REP7-1 is calculated based on percentage of recycled materials used for cavity insulation (not rigid foam insulation) (CIn). The boundary conditions are: if CIn = 0% then PL = 0; and if CIn = 20% and more, then PL = 100. Thus, the following PLF was established to calculate the PL of this sub-SPI:

$$PL_{REP7\text{-}1} = 500(CIn) \qquad 0 \le CIn \le 20\% \qquad [5.63]$$

Sheathing (REP7-2)

Likewise, using REP7-2, the amount of recycled, FSC- certified or reclaimed materials used for sheathing of the roof, floor, and wall assemblies (*Sh*), is evaluated. By applying the boundary conditions for the *Sh* data variable, the following linear PLF was established for calculating the performance level of this sub-SPI:

$$PL_{REP7\text{-}2} = 166.67(Sh) \qquad 0 \le Sh \le 60\% \qquad [5.64]$$

Once the PLs of the two sub-SPIs are calculated, the PL of the parent SPI can be calculated as:

$$PL_{REP7} = 0.5 \times PL_{REP7\text{-}1} + 0.5 \times PL_{REP7\text{-}2} \qquad [5.65]$$

5.3.4.8 Other components' content (REP8)

Cabinets, counters, and doors are components that are installed in a building at the final stages of the construction phase and account for considerable amount of materials in the building. The REP8 SPI examines the environmentally responsible materials in these components using three sub-SPIs.

Cabinets (REP8-1)

The first sub-SPI investigates the percentage of the recycled, FSC-certified or reclaimed, and composite materials in the building's cabinets (*Ca*). Based on expert consultations, the boundary conditions for *Ca* data variable were adjusted to suit the construction circumstances in BC as: if *Ca* = 0%, then *PL* = 0; and if *Ca* = 75% and up, then *PL* = 100. Therefore, the PL of REP8-1 can be calculated as:

$$PL_{REP8\text{-}1} = 133.33(Ca) \qquad 0 \le Ca \le 75\% \qquad [5.66]$$

Counters (REP8-2)

By the second sub-SPI, the recycled, FSC-certified or reclaimed, and composite materials in the building's counters (*Co*) including kitchens and bathrooms is investigated. The boundary conditions for the *Co* variable were set as: if *Co* = 0%, then *PL* = 0; and if *Co* = 70% and up, then *PL* = 100. Subsequently, the function below can be used to measure the PL of REP8-2:

$$PL_{REP8\text{-}2} = 142.86(Co) \qquad 0 \le Co \le 70\% \qquad [5.67]$$

Doors (REP8-3)

Through this sub-SPI, the use of environmentally friendly materials in doors and trims (Do), excluding garage or insulated doors, is checked. The same boundary conditions reported in LEED Canada for Homes, i.e., if Do = 0%, then PL = 0; and if Do = 80% and up, then PL = 100, were used to develop the PLF for this sub-SPI as follows:

$$PL_{REP8\text{-}3} = 125(Do) \qquad 0 \leq Do \leq 80\% \qquad [5.68]$$

By having the calculated PLs and weights of the three sub-SPIs, the parent SPI can be calculated. The weights of all sub-SPIs have been reported equal in the literature and this was confirmed by the experts in this research (CaGBC 2009). Therefore, the performance of REP8 can be measured as:

$$PL_{REP8} = 0.333 \times PL_{REP8\text{-}1} + 0.333 \times PL_{REP8\text{-}2} + 0.333 \times PL_{REP8\text{-}3} \qquad [5.69]$$

5.3.4.9 Relative importance of the SPIs under REP

The weights of the discussed REP SPIs have been determined using the literature by the focus on the sources these SPIs adopted from. Table 5.7 lists the relative importance weighs of the eight SPIs under REP.

Table 5.7 Weight set of the SPIs under the RM SPC

SPI	Weight	SPI	Weight	SPI	Weight
REP1	0.118	REP4	0.118	REP7	0.118
REP2	0.176	REP5	0.058	REP8	0.176
REP3	0.118	REP6	0.118		
					Sum = 1

5.3.5 Site Disruption and Appropriate Strategies (SD)

Construction projects such as building projects may have negative environmental and social impacts on the project site. The social impacts of the construction activities consist of negative consequences on surrounding neighborhoods and families, such as construction noise, traffic congestion, and dust, among others (Kamali and Hewage 2017b). The social impacts of building construction on the project site were discussed earlier in the previous chapter under the SPC 'Community disturbance (CD)'. This SPC was ranked 2nd among the social SPCs which indicates the experts' concern about the influence of choosing on-site and off-site construction methods on the project surroundings (see Table 4.6 in Chapter 4). However, as stated before, the social performance assessment is beyond the scope of this research. As for the environmental impacts, appropriate strategies should be implemented to minimize the site disruption due to the construction activities. Examples of such strategies are promoting natural biodiversity (e.g., providing adequate open space), planning for stormwater management, avoiding blocking fresh air or sunlight or natural waterways for adjacent developments, and so forth.

Different sources have addressed site disruption as one of the key criteria towards sustainable construction that needs to be carefully addressed (REAP 2014; BRE 2016; CaGBC 2009; USGBC 2018; GBI 2014). The 'Site disruption and appropriate strategies (SD)' SPC in this research; therefore, is intended to decrease the negative environmental impacts of residential single-family building projects on the final project site. As illustrated in Figure 5.7, this SPC comprises five SPIs, some of which consist of a number of sub-SPIs.

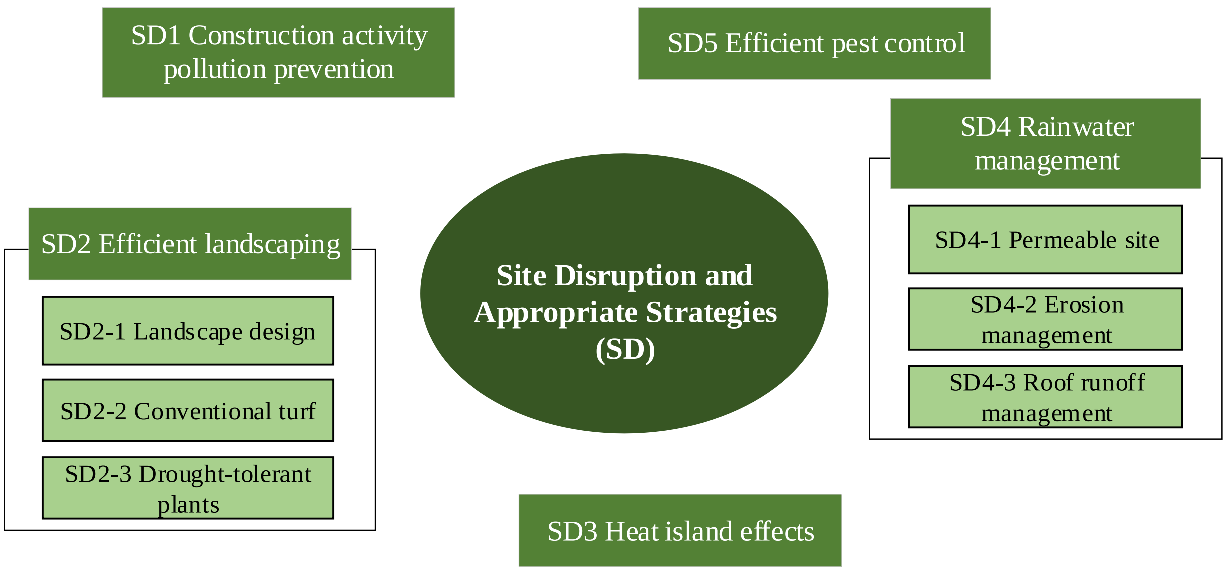

Figure 5.7 SPIs and sub-SPIs associated with 'Site disruption and appropriate strategies'

At first, it might seem that there should not be a difference between the modular and conventional construction methods with respect to this SPC. However, due to short duration of on-site activities, modular construction might have different impacts than conventional construction in terms of site disruption. As seen in the previous chapter, the participating experts were concerned if suitable strategies are implemented in modular building projects to minimize such impacts by rating the SD SPC as a 'Medium' importance criterion which is more applicable than 'Low' (see Table 4.4 in Chapter 4).

5.3.5.1 Construction activity pollution prevention (SD1)

A building is constructed on a lot, which means the natural land should be replaced with man-made buildings. Therefore, the construction of a building and the corresponding activities can cause long-term environmental impacts (i.e., damage and pollution) on the project site. This SPI examines suitable actions that if implemented, these impacts can be minimized.

Every building project is constructed on either not previously developed site or previously developed site. Depending on whether the project site is previously developed or not, the following pollution prevention actions should be checked to identify the performance of a building with respect to this SPI (USGBC 2018; CaGBC 2009):

Not previously developed sites

a) Develop a tree/plant preservation plan with "no-disturbance" zones outlined on both drawings and site.

b) Leave the minimum of 40% of buildable lot area (excluding under roof area) as undisturbed.

Previously developed sites

c) - Develop a tree/plant preservation plan with "no-disturbance" zones outlined on both drawings and site.

- Restore the undisturbed portion of the lot by undoing any previous soil compaction.
- Remove existing invasive plants.
- Use drought-tolerant turf in the landscape design (no turf in densely shaded areas or areas with more than 4:1 slope). In addition, use mulch or soil amendments as appropriate. Moreover, till all compacted soil (e.g., by construction equipment) to at least 6 inches.

d) Build on site with a lot area of less than 0.06 hectares (600 m^2), or with a housing density of one units per 0.06 hectares.

Consequently, the PL of this SPI can be measured by the following PLF:

$$PL_{SD1} = 50n + 100m \qquad n = 0, 1, 2; m = 0, 1 \qquad [5.70]$$

Where *n* is the number of implemented actions ('a' and 'b') implemented on previously developed sites and *m* is 1 if either 'c' or 'd' was implemented on not previously developed sites.

5.3.5.2 Efficient landscaping (SD2)

The SD2 SPI considers the design of landscape features by which invasive species are avoided and demand for water and synthetic chemicals is minimized. The SPI includes three sub-SPIs: 'SD2-1 Landscape design', 'SD2-2 Conventional turf', and 'SD2-3 Drought-tolerant plants'.

Landscape design (SD2-1)

This sub-SPI investigates if any of the following landscape design items have been incorporated in the design of a building (USGBC 2018; CaGBC 2009):

a - Any turf must be drought-tolerant.

b - Do not use turf in densely shaded areas.
c - Do not use turf in areas with a slope of 4:1.
d - Add mulch or soil amendments as appropriate.
e - Till all compacted soil (e.g., by construction equipment) to at least 6 inches.

If at least four of the above requirements have been considered in a building design, its performance is excellent. Thus, the PLF for this SD2-1 was established as:

$$PL_{SD2\text{-}1} = 25n \qquad n = 0, 1, 2, 3, 4 \qquad [5.71]$$

Where *n* is the number of items 'a' to 'e' that have been included in the building's design.

Conventional turf (SD2-2)

The second sub-SPI under SD2 seeks reduction of the use of traditional (chemical) turf (even drought-tolerant turf) in the softscape. Conventional lawns, as opposed to natural lawns, need significant amounts of energy and water while polluting water and air and making noise. This means the less conventional turf used in the landscape softscape results in better long-term performances; hence, the corresponding PLF should be a monotonically decreasing function. The maximum percentage of conventional turf (*CT*%) provided by LEED has been tweaked with the help of experts as: if *CT* = 60% or more, then *PL* = 0, and if *CT* = 20% or less, then *PL* = 100. Subsequently, the following PLF was developed to calculate the PL of the SD2-2 sub-SPI:

$$PL_{SD2\text{-}2} = -1.667(CT\%) + 133.34 \qquad 20 \le CT\% \le 80 \qquad [5.72]$$

Drought-tolerant plants (SD2-3)

The last sub-SPI under SD2 discusses installation of drought-tolerant plants that can result in less environmentally negative impacts. The boundary conditions determined for the percentage of drought-tolerant plants (*DTP*%) in the building's landscape as: if *DTP* = 0%, then *PL* = 0, and if *DTP* = 90% or more, then *PL* = 100. Consequently, the PL of SD2-3 is obtained as:

$$PL_{SD2\text{-}3} = 1.111(DTP\%) \qquad 0 \le DTP\% \le 90 \qquad [5.73]$$

After calculating the PLs of the three sub-SPIs above, the PL of the corresponding SPI can be measured. The weights of SD2-1, SD2-2, and SD2-3, have been determined as 0.286, 0.428, and 0.286, respectively (CaGBC 2009). Therefore, the SD2 SPI is calculated as:

$$PL_{SD2} = 0.286 \times PL_{SD2\text{-}1} + 0.428 \times PL_{SD2\text{-}2} + 0.286 \times PL_{SD2\text{-}3} \qquad [5.74]$$

5.3.5.3 Heat island effects (SD3)

In the past few decades, the urban areas have been significantly developed by replacing open and permeable lands with different buildings and infrastructure. Therefore, the urban areas have become warmer than their rural surroundings forming an island of higher temperatures called heat island (EPA 2018a). The temperature differences between urban surfaces (e.g., pavements, roofs) and the air range between 27 to 50°C in the summer, while there is no difference between the temperature of the surfaces and the air in rural areas. Heat island has negative impacts on human, microclimates, and wildlife habitats (Berdahl and Bretz 1997; EPA 2018a).

To minimize the heat island impacts, a number of landscape features can be designed at the design stage of a building such as shading hardscapes around the building. The intent of the SD3 SPI is to assure consideration of such landscape features. According to both Canadian and US versions of LEED for single-family homes (USGBC 2018; CaGBC 2009), implementation of either of the following options can satisfy the requirement for reduction of the heat island effects:

Option 1- Use trees or other plantings by which shading is provided for over half of the patios, sidewalks, and driveways within 50 ft of the building.

Option 2- Install non-absorptive materials such as light-colored, high-albedo materials, or vegetation-covered hardscapes (white concrete, open pavers, materials with solar reflectance index ≥ 0.29) for over half of the patios, sidewalks, and driveways within 50 ft of the building.

Consequently, the PLF for this SPI was established as:

$$PL_{SD3} = 100n \qquad n = 0, 1 \qquad [5.75]$$

Where n is 1 if either of the Options 1 or 2 has been considered and implemented.

5.3.5.4 Rainwater management (SD4)

Site features should be incorporated in the design stage such that the erosion and runoff volume from the project site is minimized. This SPI investigates whether a building meets the requirements for suitable rainwater management. It consists of three sub-SPIs including ‘SD4-1 Permeable site’, ‘SD4-2 Erosion management’, and ‘SD4-3 Roof runoff management’.

Permeable site (SD4-1)

This sub-SPI checks the permeable portion of the building’s lot. The lot should be designed in a way that the majority of the buildable land (excluding the area under roof) is permeable or designed to capture water runoff for infiltration on the lot. Areas that are considered permeable land include (CaGBC 2009):

a. Vegetative landscape (e.g., trees, grass).

b. Permeable paving, installed by an experienced professional. Permeable paving must include porous above-ground materials (e.g., open pavers, engineered products) and a 6-inch porous subbase, also the base layer must be designed to ensure proper drainage away from the home.

c. Impermeable surfaces that are designed to direct all runoff toward an appropriate permanent infiltration feature (e.g., vegetated swale, on-site rain garden, or rainwater cistern).

According to the literature and expert consultations, the boundary conditions for the percentage of permeable land ($PeL\%$) were set and then the following PLF was established for SD4-1:

$$PL_{SD4\text{-}1} = 2.5(PeL\%) - 150 \qquad 60 \leq PeL\% \leq 100 \qquad [5.76]$$

Erosion management (SD4-2)

This indicator determines whether suitable measures for permanent erosion controls have been designed. A building shows excellent performance if either of the following measures has been designed and implemented (USGBC 2018; CaGBC 2009):

Option 1- In case the site is located on a steep slope, install terracing and retaining walls to decrease the long-term runoff effects.

Option 2- Plant one tree, four 19-litre (5-gallon) shrubs, or 4.6 square meters of native groundcover per 46 m^2 of disturbed lot area (including area under roof).

Thus, the performance level of this SPI can be measured using the PLF below:

$$PL_{SD4\text{-}2} = 100k \qquad k = 0, 1 \qquad [5.77]$$

Where k is 1 if either Options 1 or 2 for permanent erosion controls has been implemented.

Roof runoff management (SD4-3)

To control and manage the runoff from the roof of a building, appropriate strategies should be followed. The third sub-SPI under the SD4 SPI, evaluates the performance of a building with respect to such strategies. Following are a number of measures that if designed and installed, the quality management of runoff from the building roof is achieved:

a. Installation of vegetated roof with roof coverage ≥ 50%.

b. Installation of vegetated roof with roof coverage ≥ 100%..

c. Installation of permanent stormwater controls such as vegetated swales, on-site rain garden, dry well, or rainwater cistern.

d. Site design by licensed landscape designer or engineering professional such that all water runoff from the building is managed through an on-site design element.

Consequently, the PL of the building with respect to SD4-2 can be presented as:

$$PL_{SD4\text{-}3} = Min\{100,\ 25i + 50j + 100k\} \qquad i = 0, 1; j = 0, 1, 2; k = 0, 1 \qquad [5.78]$$

Where i is 1 if measure 'a' was met, j is the number of measures 'b' and 'c' that were met, and k is 1 if measure 'd' was met.

Eventually, the calculated PLs of these sub-SPIs and their weights are combined to evaluate the performance of the subject building with respect to the SD4 SPI as:

$$PL_{SD4} = 0.571 \times PL_{SD4\text{-}1} + 0.143 \times PL_{SD4\text{-}2} + 0.286 \times PL_{SD4\text{-}3} \qquad [5.79]$$

5.3.5.5 Efficient pest control (SD5)

This SPI deals with the design features by which the need for pest control chemicals is minimized to reduce the pest problem and also the risk of exposure to poisons (USGBC 2018). The performance the building with respect to the SD5 indicator is calculated based on implementation of the measures specified below (CaGBC 2009):

a- All wood (e.g., siding, structure) should be more than 1ft above soil.

b- All external cracks, joints, penetrations, edges, and entry points should be sealed with caulking. Use rodent- proof and corrosion-proof screens (e.g., copper or stainless-steel mesh) where openings cannot be caulked or sealed.

c- Use no wood-to-concrete connections or separate any exterior wood-to-concrete connections (e.g., at posts, deck supports, stair stringers) with metal or plastic fasteners or dividers.

d- Install landscaping such that all parts of mature plants are at least 2 ft from the building.

Therefore, the following PLF was established to calculate the PL of SD5:

$$PL_{SD5} = 25n \qquad n = 0, 1, 2, 3, 4 \qquad [5.80]$$

Where n is the number of implemented pest control measures (listed above) on the project site.

5.3.5.6 Relative importance of the SPIs under SD

The SPIs used under the SD SPC have been mentioned in different sources using diverse wording and descriptions. However, since all of the five SPIs are available in both Canadian and the US versions of LEED, these references were used to determine the weights of these SPIs. In doing so, the weight of each SPI has been determined by normalization of the maximum available points of the SPI to the total available points of all five SPIs. Therefore, the weights of SD1, SD2, SD3, SD4, and SD5, came to be 0.056, 0.389, 0.056, 0.389, and 0.111, respectively.

5.3.6 Renewable Energy Use (RE)

The ‘Renewable energy use (RE)’ SPC evaluates the performance of residential buildings with respect to the use of renewable energy sources during the use phase. In addition to the negative environmental consequences of non-renewable natural resource consumption, such as land, air, and water pollution, another important result is negative social impacts such as health and occupational issues (Palaniappan 2009). Despite finite fossil fuels, renewable energy sources regenerate. There are various forms of renewable energy sources including solar, hydropower, geothermal, biomass, and wind (EIA 2018).

Currently, Canada ranked first globally in the production and use of renewable energy due to its diverse renewable resources to generate a significant portion of the total energy need. Canada obtained 17.4% of its primary energy supply from renewable sources in 2016 (currently 18.9%), while the world average was around 13% (NRC 2018c; NRC 2017c).

In buildings, renewable energies can be used for space heating, water heating, and electricity (e.g., lighting, appliances) (NRC 2017c). The ultimate goal of using renewable energy sources in buildings is to reach the level of net-zero energy building (NZEB), also called zero-energy building and zero net energy. In a NZEB, the total annual energy consumed by a building approximately equals the renewable energy generated on site or supplied off site by renewable energy sources (Pless and Torcellini 2010; Peterson et al. 2015; Torcellini et al. 2006). Detailed definitions and classifications of NZEB buildings have been provided in Appendix E.

Although NZEB homes are technically feasible, they are not yet affordable and common for average homebuyers (NRC 2018c). Consequently, a building’s performance with regard to the RE SPC is evaluated based on the renewable energy share of the total energy consumption in regular (not custom made or luxurious) single-family buildings that can be produced on-site or purchased off-site. Three SPIs were recognized under this SPC: ‘RE1 Renewable electricity’, ‘RE2 Renewable space heating’, and ‘RE3 Renewable water heating’ as shown in Figure 5.8.

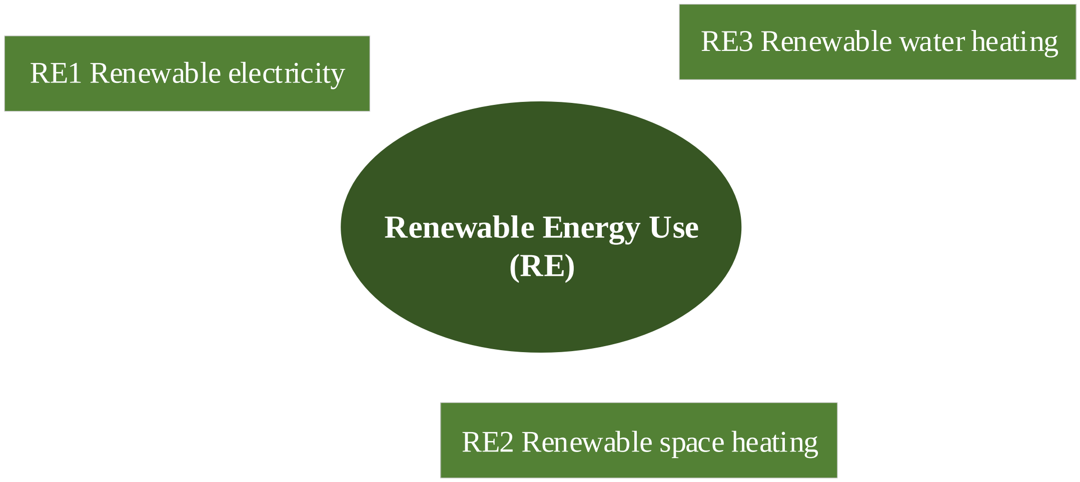

Figure 5.8 SPIs associated with 'Renewable energy use'

5.3.6.1 Renewable electricity (RE1)

The intent of this SPI is to reduce the demand for non-renewable energy in residential buildings by increasing the use of renewable electricity. The province of BC has the potential to be the world leader in evolving sustainable energy technologies as effective energy alternatives (Evans 2008). When it comes to electricity, almost 95% of the power supply is renewable sources including both large-scale and small-scale hydroelectric power (BC's big dams and rivers), significant potential for wind power, geothermal, and marine energy (NEB 2017; BCSEA 2018; BC Hydro 2018). However, this does not mean that 95% of every home's electricity in BC is supplied by renewable sources, because the portion of renewable sources to generate electricity are different among the electricity providers. Furthermore, in almost everywhere in BC that a building is built, the choice of an electricity provider is limited to only one and this is independent from the construction method. Installation of renewable electricity generation systems in a building can reduce the dependency on the electricity supplied by official providers. This offers three advantages. The first advantage is to increase the building's renewable electricity sources, which results in less environmental impacts due to electricity consumption. The second advantage, however, is economic. Many electricity providers around the world bill their residential electric customers on a multiple-tier rate. For example, ForticBC, as an electricity provider in parts of the Okanagan, has set a two-tire rate for the electricity cost, which means that if a building consumes above a certain amount, each unit of electricity will cost more than regular price. Therefore, using renewable electricity generation systems can offset a portion of power need in a building. Lastly, as the third advantage, it raises the building's value.

Solar energy is a significant renewable energy source that each building can use to supply the energy needed for heating and electricity (NRC 2017c). Solar power systems, also called photovoltaic or PV systems, are the main renewable electricity generation systems. These systems convert sunlight to electricity PV arrays that can be placed on or beside the building (Hayter and Kandt 2011). In 2019, BC has been ranked as Canada's seventh province for solar power (Energyhub 2019). The Okanagan Valley in BC is amongst the best regions for solar power systems within the province (due to its sunny days) where it is possible to offset all of the power needs in the summer and a sizeable portion in the winter. Although the cost of a PV system has significantly dropped in the past few years (BC Hydro 2018), it is not still a desirable option. However, in a long term view, it is economical because PV systems have a warranty of 25-30 years and the payback of a typical system is approximately 12 years, which means 13-18 years (and more) of free electricity (Terratek Energy 2017).

To evaluate the performance of a building with regard to this SPI, both the energy supplied by the renewable electricity generation systems (other than BC power supply) and the annual reference electrical load should be estimated. The annual reference electric load can be estimated by the HERS Reference Home or the EnerGuide reference for average size homes. Thus, the building's renewable electric load ratio (*REL*%) is calculated as:

$$REL\% = \frac{Annual\ electricity\ supplied\ by\ renewable\ energy\ sources}{Annual\ electricity\ consumption\ in\ reference\ home} \qquad [5.81]$$

Consequently, using the upper boundary condition of *REL*% = 30% for *PL* = 100 (CaGBC 2009), the following PLF was proposed to measure the RE1 SPI:

$$PL_{RE1} = 3.33(REL\%) \qquad 0 \leq REL\% \leq 30 \qquad [5.82]$$

5.3.6.2 Renewable space heating (RE2)

Another application of renewable energy is heating the internal space of buildings. According to Natural Resources Canada, in 2015, approximately 40.8% of the energy consumed for space heating in BC residential buildings was supplied by renewable energy sources and the remaining was supplied by non-renewable energy sources mainly natural gas (52.1%) and heating oil (3.4%) (NRC 2015a). Therefore, there is a large room for replacing non-renewable energy sources (fuel-source options) by renewable sources (electricity, solar) for space heating in BC.

Solar energy is an important source that each building can use to supply the energy needed for heating and electricity. Space heating by solar energy is gaining attention in some parts of the world. For example, the Solar Thermal Industry Federation in Europe anticipated that up to 50% of all space heating will be provided via stored solar heat by 2030 (NRC 2017c). However, in Canada, solar thermal systems are installed mostly for water heating instead of space heating.

This is probably why these systems have not been appreciated in rating systems such as LEED Canada for Homes, whereas the use of solar hot water and solar power systems in a building can earn up to approximately 2.5% and 8% of the total available credits in LEED, respectively.

According to BC Hydro (2018), based on the climate conditions, a solar thermal system may be less economical than other fuel-sources for space heating of Canadian buildings. To decide whether a solar thermal system is a suitable option for a residential building, a number of factors should be considered including utility rate for heating, the duration of heating season, and the surface area of roof and south facing wall to install the heat collector panels (Hayter and Kandt 2011). As stated before, solar systems can effectively installed in the Okanagan because of its numerous hot and sunny days. For example, Kelowna sees more sunny days than almost any other Canadian city, with over 300 days of sunshine (2000 sunlight hours) each year (Environment Canada 2018). Therefore, solar thermal systems for space heating can be a potential option in the Okanagan to offset a portion of energy required for heating homes.

During the screening process to determine the measurement method of the RE3 SPI, no studies or reports were found that discussed and evaluated the solar thermal systems for space heating. Therefore, the following PLF was proposed as a basis to calculate the PL this SPI:

$$PL_{RE2} = 100n \quad n = 0, 1 \qquad [5.83]$$

Where n is 1 if a solar thermal system is installed in the building.

5.3.6.3 Renewable water heating (RE3)

Water heating consumes a significant portion of the total energy consumption in buildings (including residential) worldwide. In 2015, the energy used for water heating in residential buildings in Canada and its BC province has been reported as 18.7% and 25.1% of the total energy consumption of these buildings, respectively (NRC 2015b; NRC 2015c).

According to Natural Resources Canada, in 2015, less than 25% of the energy required for water heating of the BC residential buildings was supplied by renewable energy sources (NRC 2015d). Solar systems for water heating use the sun's energy as an alternative energy source to electricity or gas, to heat water with zero pollution, zero fuel costs, and insignificant operation and maintenance costs. These systems are able to supply up to approximately 80% of hot water demand. Although the application of the solar heating is still limited, e.g., maximum 1% of the potential water heating market in the US (Walker 2016), it has begun to grow in the past few years. For example, Solar BC (2008) reported at least 540 residential solar hot water systems in BC before 2008 and this number is expected to continue rising. Aside from solar systems, high efficiency electric water heating systems can also be another renewable water heating option in

BC. It might appear contradictory to efforts undertaken above to use solar power systems in order to offset a portion of the electricity supplied by electricity providers. However, using electric water heating systems is more sustainable than non-renewable energy sources for water heating since approximately 95% of the electricity in BC supplied by renewable energy sources (NEB 2017; BCSEA 2018; BC Hydro 2018).

Consequently, the RE3 SPI can be evaluated based on installation of any of the water heating systems under the three groups listed in Table 5.8.

Table 5.8 Renewable water heating systems

Group	Water heating system
G1	- High-efficiency storage electric water heater with EF (energy efficiency) ≥ 0.89 (300 litres / 80 gallons) - Solar heat exchanger that absorbs waste heat from drain water to pre-heat domestic hot water
G2	- Tank less electric water heater with EF ≥ 0.99 - Solar water heater (with preheat tank) that supplies 40% ≤ annual domestic hot water load ≤ 60%
G3	- Electric heat pump water heater (ground- or air-sourced) with EF ≥ 2.0 - Solar water heater (with preheat tank) that supplies annual domestic hot water load ≥ 60%

The following PLF can be used to calculate this SPI:

$$PL_{RE3} = \begin{cases} 0 & none\ of\ systems \\ 33.3 & one\ of\ G1\ systems \\ 66.7 & one\ of\ G2\ systems \\ 100 & one\ of\ G3\ systems \end{cases} \quad [5.84]$$

5.3.6.4 Relative importance of the SPIs under RE

The RE performance of a building can be calculated by combining the calculated PLs of the associated SPIs and their weights. According to the literature and expert consultations, the weights of ER1, ER2, and ER3, were determined as 0.667, 0.133, and 0.2, respectively.

5.3.7 Greenhouse Gas Emissions (GE)

Human intensive activities such as production of different products, deforestation and land-use changes, consumption of finite natural resources (e.g., fossil fuels), and transportation, lead to the emissions of so-called greenhouse gases (GHGs) that cause negative environmental impacts. A huge amount of GHG emissions (up to 50% of the global release) is due to the activities related to the building sector (CIWMB 2000). Therefore, quantification of GHG emissions can assist with the identification and management of responsible decisions, activities, and operations in this sector. This leads to the environmental impact mitigation, quality asset management, and cost savings and (BC ECCS 2017).

In Canada, GHG emissions have increased by 16.7% from 1990 to 2016 (BC ECCS 2018; CCC

2016). However, Canadian provinces accounted for different shares of the total GHG emissions. According to BC ECCS (2018), the GHG emissions in BC has increased by 17.6%, which is above the average national increase.

Global warming is among the most important environmental impacts resulted by GHGs (Asif et al. 2007). The global warming potential (GWP) measure, also called “carbon footprint” or “embodied carbon results”, is used to quantify the role of a GHG substance in climate change. According to the literature, not only global warming, but other environmental impacts such as ozone depletion, smog, and so forth, are also important and should be paid attention to. Thus, the SPC ‘Greenhouse gas emissions (GE)’ analyzes a number of important environmental impacts incurred in the material production phase and the construction phase (collectively called cradle-to-gate) of modular and conventional buildings. To this end, this research measured the selected environmental impacts using the life cycle assessment (LCA) method and then developed a set of environmental impact indices using an AHP-based framework. The developed impact indices can be used for comparisons of the environmental impacts of selecting different construction method (i.e., modular versus conventional) during cradle-to-gate of their life cycle.

5.3.7.1 Life cycle assessment

According to the US Environmental Protection Agency (EPA 2001), the life cycle assessment (LCA) is a “cradle-to-grave” approach that investigates the environmental impacts of a product or process during the apparently separate but practically inter-dependent life cycle phases. LCA is an important analytical method for estimating the environmental impacts caused by all stages of a life cycle phase, even those not included in many traditional assessments, such as raw materials acquisition, materials transportation, end of life disposal, and so forth (Trusty 2010; SAIC 2006; ISO 2006a). Consequently, LCA provides a holistic picture of a product/process’s environmental impacts, which can assist the decision makers with making informed decisions on trade-off between different product and process options. For example, LCA quantify and reports GWP to indicate the extent to which a building, over its lifetime, may contribute to climate change. It is important to note that, depending on the goal and scope of a research study, a partial LCA is conducted by covering limited number a product’s life cycle phases and also particular activities/tasks within the covered phases.

The LCA methodology consists of the following four stages (ISO 2006a; ISO 2006b):

1- Goal and scope definition;
2- Life cycle inventory (LCI) analysis;
3- Life cycle impact assessment (LCIA); and

4- Interpretation.

Stage 1 consists of defining the objectives, functional unit, and system boundary of the LCA study. In the case of buildings, according to BS EN 15978 (BSI 2011), a functional equivalent is “the quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison.” In other words, the functional equivalent is a set of design criteria that both buildings must have in common to ensure an apples-to-apples comparison (Bowick and O'Connor 2017).

Stage 2 involves collecting the required data and calculating the related inputs and outputs using the LCI database. In Stage 3 the potential environmental impacts categories, such as GWP, based on the results of the previous stage (i.e., LCI analysis) are calculated. Finally, in Stage 4 the results of LCI and LCIA analyses are interpreted (ISO 2006a; ISO 2006b).

LCA is a complicated process in the construction industry including the building sector. It is not an easy task to collect the necessary data and produce generalizable results, mainly due to the highly “decentralized nature” of the construction industry, various material types, jobsite specifications, different assembly methods, and so forth (Malin 2005; Kohler and Moffatt 2003; Priemus 2005).

5.3.7.2 Definition of goal and scope

The first stage of every LCA study is to define the study objectives, functional unit, and system boundary. The objective of the LCA in this research was to analyze, compare, and contrast the environmental impacts of single-family buildings constructed by traditional on-site and modular off-site construction methods. The benchmarking case study buildings included two modular and one conventional single-family buildings designed and constructed in the Okanagan, BC. The LCA was partial which covered the cradle-to-gate life cycle of the buildings including the material production phase and the construction phase. In other words, the LCA performed in this study included the materials and energy associated with the production of raw materials to the finished building and excluded the materials and energy associated with the use and end of life phases. Therefore, any materials and energy required for the operations (i.e., utilities, furniture, and appliances), maintenance (i.e., repair, replacement, renovation), and end of life (i.e., waste management strategies) of the case study buildings were not included in the LCA process. The functional unit was set at the construction of 1 ft^2 of average-quality single-family building in the Okanagan, BC (Table 5.9).

Table 5.9 Functional equivalent set of LCA in this research

	Functional criteria
Building type	single-family residential
Structure system	one story, wood
Location	Okanagan, BC
Service life (yrs.)	60
Functional unit	1 ft^2 of the total floor area
Total floor area (ft^2)	under 3000
Covered life cycle phases	production phase, construction phase

5.3.7.3 Required data for inventory analysis

After defining the goal and scope of the study, the next step was to collect the material and energy data of the case study buildings for inventory analysis. The inventory flows should appropriately reflect the regional or national practices for a product or service. Since the general focus of this research is on the residential buildings located in Canada, the Athena Impact Estimator for Buildings software (v5.3.0111) was utilized for the life cycle inventory (LCI) and the subsequent life cycle impact assessment (LCIA) of the LCA in this research. Developed by Athena Sustainable Material Institute, the Athena LCI database has been designed to evaluate buildings based on the LCA methodology. Athena has developed a set of regional databases for key building materials, products, processes, and energy information, applicable to typical commercial, industrial, and residential buildings in different locations throughout North America (Athena 2018; Bowick and O'Connor 2017).

In this research, the activities related to the material production phase and the design and construction phase (henceforth the construction phase) were categorized into four activity categories as:

- Material production phase: (A1) Material extraction and process; and (A2) Material transportation.
- Construction phase: (A3) Construction and installation; and (A4) Product and worker transportation.

To perform the inventory analysis, the data of material and energy associated with these activity categories should be collected for each benchmarking building from the corresponding homebuilder. The required data variables (raw data) of each activity category have been summarized in Table 5.10 and described as follows.

Table 5.10 Required data for inventory analysis

Construction method	Activity category	Data variable
Conventional & modular	A1, A2	Materials and products (types, quantities)
Conventional	A3	On-site energy (machinery, heating, cooling)
Conventional	A4	Worker transport (number, workdays, commute modes) Material/product transport (supplier-site distances, transport modes)
Modular	A3	Off-site energy (machinery in factory, heating, cooling) On-site energy (machinery for site work, heating, cooling)
Modular	A4	Worker transport to factory (number, workdays, commute modes) Worker transport to site (number, workdays, commute modes Material/product transport to factory (supplier-factory distances, transport modes) Module transport (factory-site distance, transportation mode)

<u>Material production phase</u>

As mentioned above, the material production phase accounts for energy consumed in the following activity categories:

A1) Material extraction and process. First, the primary resources (i.e., raw materials) such as wood and iron ores are harvested/extracted. Then, they are converted into processed materials and engineered products usable for certain construction purposes such as lumbar plates, steel bars, windows, and so forth.

A2) Material transportation. The extracted raw materials are shipped to the manufacturing plant gates for processing.

It is important to mention that the information about the energy used for the above activity categories in a region (e.g., BC) is embedded in the Athena LCI database. Therefore, the required data variables (raw data) are the bill of materials/products and their quantities used in the case study buildings.

<u>Construction phase</u>

The materials and products produced in the previous phase should be transported to the project site for construction of the building. Because the construction phase substantially differs between the conventional and modular construction methods, the activity categories correspond to this phase (A3 and A4) comprise different tasks in the case of each construction method.

The construction phase of conventional construction accounts for energy consumed in the following activity categories:

A3) Construction and installation. This category comprises all on-site activities lead to the construction of the final building on the project site (e.g., foundation, structure, flooring, roofing, finishing). The data variable for A4 includes the energy consumption (natural gas, electricity, etc.) on the project site during construct of the building including operation of construction equipment (e.g., crawler crane, skid loader) and operation of the office (e.g., heating, cooling). The Athena LCI database is able to calculate the energy correspond to the operation of construction equipment. However, the energy consumed for operation of the office should be calculated separately and fed into the software.

A4) Product and worker transportation. This category includes the delivery of the processed materials and products to the project site as well as the workforce commuting to and from the project site. Based on the bill of materials and the location of a building project, the Athena LCI database calculates the energy correspond to the material and product transportation. However, estimation of the energy consumed for employee transportation is out of the scope of the software. This energy should be calculated separately based on the number of workers on-site, the number of their working days, and their commute modes, and fed into the software.

The construction phase of modular construction accounts for energy consumed in the following activity categories:

A3) Construction and installation. The category includes all off-site activities towards fabrication of the building's modules in the modular manufacturing center (i.e., modular factory) and on-site activities related to the site work. Because of the differences of the activities under A3 between conventional and modular construction methods, the corresponding energy can also be significantly different. The Athena LCI database does not have the capability to calculate this energy for modular construction. Therefore, the energy related to A3 for a modular building project should be calculated separately. In this regard, the data of energy consumed off-site during the fabrication of modules in the modular factory such as machinery and heating, and also on-site during the site work such as foundation and module installations are required.

This should be stressed that, calculation of the energy consumed in the factory for manufacturing the modules of a specific modular building project is not an easy task. This is because in a modular factory, multiple modules are manufactures simultaneously which do not necessarily belong to one project. To resolve this issue, the total annual energy consumed in the factory can be divided by the total annual production (i.e., total floor area) to obtain the off-site energy associated with production of 1 ft^2 of a modular building.

A4) Product and worker transportation. This category comprises the delivery of the required materials and products to modular factory and the delivery of the completed modules to the project site as well as the employee's commute to and from work (off-site and on-site). In this regard, the data variables associated with A4 include the number of workers off-site (the modular factory) and on-site (the project site), the number of their working days, and their commute modes. In addition, the distances between the product manufacturing plant gates and the modular factory, the bill of materials/products consumed, and their transportation modes are required. Furthermore, the distance between the modular factory and the project site as well as the truck type to ship the modules are required.

5.3.7.4 Life cycle impact assessment

The Athena's LCIA methodology used to calculate the environmental impact measures is based on the US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) impact assessment method (Bowick and O'Connor 2017; Bare et al. 2012). Consequently, eight impact measures including global warming potential, eutrophication potential, acidification potential, ozone depletion potential, human health effect, smog potential, fossil fuel consumption, and eco-toxicity effect were calculated as described below.

Global warming potential

Global warming is among the most important environmental impact categories, which is the consequences of a long-term accumulation of GHGs in the higher layer of atmosphere (Asif et al. 2007). Global warming indicates the extent to which such human activities and the subsequent GHGs may contribute to climate change (Bowick and O'Connor 2017). The primary global warming' GHG contributors are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). While historically CO_2 has gained more attention, studies showed that CH_4 and N_2O contribute much more than CO_2 to climate change (Hermann 2017). To quantify the role of a GHG substance in climate change, the global warming potential (GWP) measure, also called "carbon footprint" or "embodied carbon", is used. It is common to express the GWP of CH_4, N_2O and other GHGs based of their equivalent GWP of CO_2 that is called carbon dioxide equivalent or CO_2eq (Demirel 2014). In other words, GWP is the ratio of the climate change caused by a GHG substance to the climate change caused by the same mass of CO_2 (Azapagic et al. 2003). Consequently, the GWP of all GHGs can be calculated and summed up based on kilograms of CO_2eq.

Acidification potential

Acidification is a regional impact that has human health impact. It occurs when high concentrations of NO_x and SO_2 are attained. Acidification potential (AP) is a measure to quantify this impact, which is represented, based on the contributions of SO_2, NO_x, HCl, NH_3, and HF to the potential acid deposition to form H^+ ions. It is common to represent the AP of these substances based on their equivalent AP of SO_2 that is called SO_2eq. The equivalent AP of a substance is the ratio of AP caused by a substance to AP caused by the same mass of SO_2 (Azapagic et al. 2003). Therefore, the AP for all of these substances can be calculated and summed up based on kilograms of SO_2eq.

Human health effect

Human health effect (HHE) due to particulate matters of various sizes (PM10 and PM2.5) have a considerable impact on human respiratory system. The US EPA identified “particulates” as the top cause of human health deterioration, due to its impact on the human respiratory system (asthma, bronchitis, acute pulmonary disease). Athena uses TRACI’s "Human Health Particulates from Mobile Sources" characterization factor on an equivalent PM2.5 basis, to calculate the sum of particulate matters released by different activities during life cycle of buildings (Athena 2016).

Eutrophication potential

The eutrophication potential (E-P) measure is defined as the potential of nutrients to cause over-fertilization of water and soil, which can result in increased growth of biomass (Azapagic et al. 2003). When a previously scarce or limiting nutrient is added to a water body, it leads to the proliferation of aquatic photosynthetic plant life. This may lead to a chain of further consequences ranging from foul odors to the death of fish. Emissions of chemicals such as NO_x, NH_4^+, N, PO_4^{3-}, P, and COD, are the main contributors to eutrophication. E-P result is expressed on an equivalent mass of nitrogen (N) basis, kg Neq (Athena 2016). The equivalent E-P of N for these chemicals can be found in the literature (Azapagic et al. 2003).

Ozone depletion potential

The ozone depletion potential (ODP) measure indicates the potential of emissions of chlorofluorohydrocarbons (CFCs) and chlorinated hydrocarbons (HCs) for depleting the ozone layer (Azapagic et al. 2003). This impact measure is expressed based on kilograms of CFC-11 using other chemicals’ equivalent ODP of CFC-11.

Smog potential

Photochemical smog is defined as “a mixture of pollutants that are formed when nitrogen oxides and volatile organic compounds (VOCs) react to sunlight, creating a brown haze above cities.” (SA EPA 2004). This is a symptom of photochemical ozone creation potential (POCP). While ozone is not emitted directly, it is a product of interactions of volatile organic compounds

(VOCs) and nitrogen oxides (NO_x). The smog potential (SP) measure is represented based on a mass of equivalent O_3 basis (kg O_3eq).

Fossil fuel consumption

Fossil fuel consumption (FFC) refers to the fossil fuel energy types including coal, diesel, feedstock, gasoline, heavy fuel oil, LPG (propane), and natural gas that are consumed as the embodied energy throughout the life cycle of a building. However, since the LCA in this study is cradle-to-gate, the calculated FFC represents the embodied energy consumption in the material production phase and the construction phase of the case study buildings. FFC is expressed in mega joules (MJ).

Eco-toxicity effect

Eco-toxicity involves the identification and quantification of the impacts of toxic chemicals on nonhuman organisms, populations, or communities. Therefore, less consumption of toxic chemicals and materials in different products can significantly reduce the eco-toxicity effects (EF). Various chemicals can affect the ecosystem; however, according to the Eco-indicator 99 impact assessment method, the eco-toxicity impact of a chemical is determined based on its damage factor, i.e., potentially affected fraction of species in an environment (PAF, in m2year per kg) (Goedkoop and Spriensma 2001; Viveros Santos et al. 2018). Diverse high PAF chemicals have been reported in the literature (Goedkoop and Spriensma 2001). However, the results of the inventory analysis in this research showed that during the material production and the construction phases of the case study buildings, only seven high PAF chemicals have been released to the environment. Therefore, these toxic substances were considered as the main contributors to eco-toxicity in this research and their PAF values (reported in Eco-indicator 99) were used to determine their importance weights as shown in Table 5.11.

Table 5.11 Weights of the main contributing chemicals to eco-toxicity

Toxic substance	PAF (m2yearkg-1)	Normalized weight
Arsenic	1.14E+02	0.011
Cadmium	4.80E+03	0.451
Chromium	6.87E+02	0.065
Copper	1.47E+03	0.138
Mercury	1.97E+03	0.185
Nickel	1.43E+03	0.134
Zinc	1.63E+02	0.015

Therefore, eco-toxicity effect of a give building can be calculated as:

$$EE = \sum_{k=1}^{7}(m_{sk} \times w_{sk}) \qquad [5.85]$$

Where m_{sk} is the mass of substance k calculated by inventory analysis and w_{sk} is the normalized weight of the substance (Table 5.11).

5.3.7.5 Development of environmental impact indices

By performing LCIA, each of environmental impact measures can be quantified and compared individually between the modular and conventional buildings to benchmark their performance with respect to the corresponding environmental impact. In addition to such comparisons, it is useful to collectively compare the overall environmental impact using a single measure, which is based on all the eight environmental impact measures.

To this end, this research developed a set of environmental impact indices for buildings. An AHP-based framework was used to aggregate various environmental impact measures into a set of unified indices for the buildings under study. The analytic hierarchy process (AHP) is one of the known and widely used MCDA methods to solve complex decision making problems consisting of numerous parameters, i.e., various criteria (attributes) and few alternatives. Invented by Saaty (1980), AHP is able to combine qualitative and quantitative criteria in a systematic decision making framework (Wedley 1990). In an AHP framework, the pairwise comparison method is used for determining the relative importance (weight) of a parameter, such as a criterion or an alternative, with regard to other parameters (Golden et al. 1989). The first critical step in construction of an AHP-based framework is to determine suitable parameters to be placed in different levels as the AHP hierarchy including primary goal, criteria and attributes (sub-criteria), and alternatives. Figure 5.9 illustrates the proposed AHP-based framework in the present study and the hierarchy of different contributing parameters.

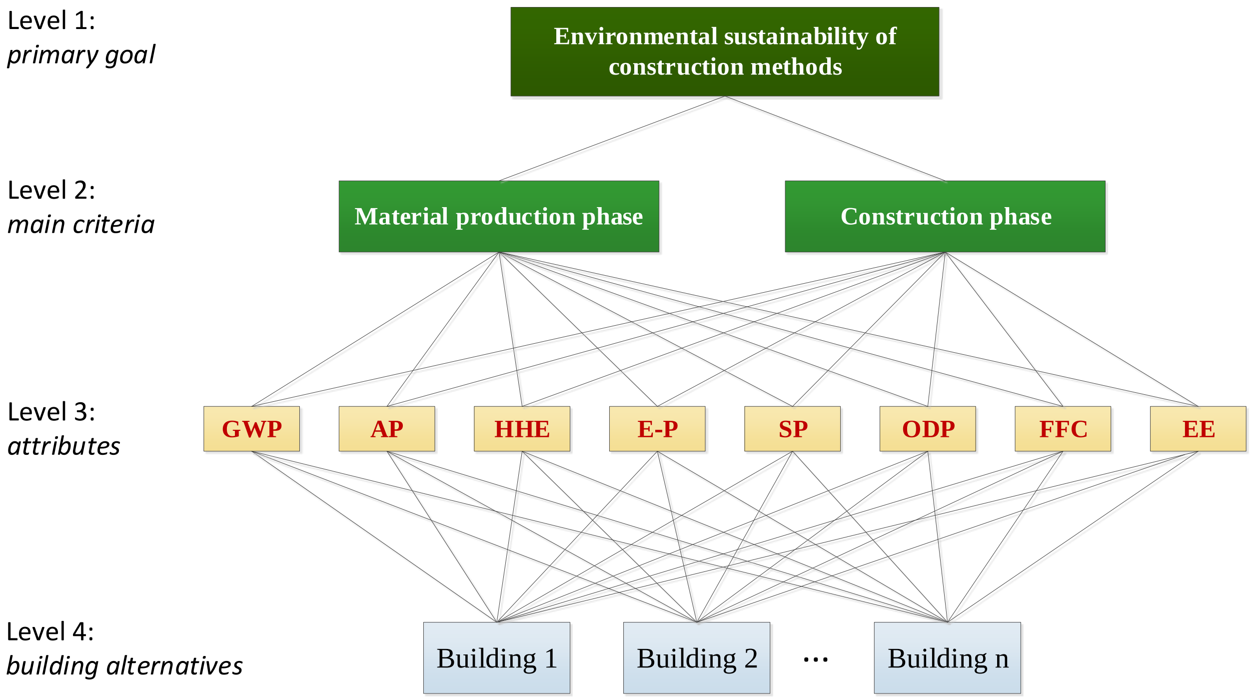

Figure 5.9 Hierarchy of AHP-based framework and contributing parameters

By using the proposed AHP-based framework, three environmental impact indices were developed for each case study building as described below.

- Material production phase index (*MPPi*): This index represents the environmental performance of each case study building in the material production phase of its life cycle. For the alternative building A, *MPPi* is calculated as:

$$MPPi_A = \sum_{i=1}^{8}(w_{mi} \times E_{mi \to MPP\ of\ A}) \qquad [5.86]$$

where w_{mi} is the relative importance weight of the *i*th measure (e.g., GWP) with respect to other impact measures and $E_{mi \to MPP\ of\ A}$ is the normalized effect of the *i*th measure on the material production phase of building A.

- Construction phase index (*CPi*): This index represents the environmental performance of each case study building in the construction phase of its life cycle. For the alternative building A, *CPi* is obtained as:

$$CPi_A = \sum_{i=1}^{8}(w_{mi} \times E_{mi \to CP\ of\ A}) \qquad [5.87]$$

where w_{mi} is the weight of the *i*th measure with respect to other impact measures and $E_{mi \to CP\ of\ A}$ is the normalized effect of the *i*th measure on the construction phase of building A.

- Cradle-to-gate index (*CTGi*): This index highlights the overall environmental performance of each case study building with respect to the whole cradle-to-gate life cycle of it. For the alternative building A, *CTGi* is presented as:

$$CTGi_{\mathrm{A}} = \sum_{i=1}^{8}(w_{mi} \times E_{mi \rightarrow CTG\ of\ A}) \qquad [5.88]$$

where w_{mi} is the weight of the *i*th measure with respect to other impact measures and $E_{mi \rightarrow CTG\ of\ A}$ is the normalized effect of the *i*th measure on the total cradle-to-gate life cycle of building A.

According to the AHP methodology, the weights of different criteria are determined using pairwise comparisons. In the lack of quantitative data for criteria, such pairwise comparisons are made qualitatively by experts (e.g., Likert scale) and the weights are then assigned to criteria. However, this way of weight assignment involves human subjectivity. In terms of the weights of the environmental impact measures (w_{mi}) in this research, the literature showed a number of weighting schemes based on expert opinions including Building for Environmental and Economic Sustainability (BEES) Stakeholder Panel and EPA Science Advisory Board (Hossaini et al. 2015). To examine the human subjectivity, a sensitivity analysis was conducted by which three weighting schemes for the environmental impact measures were applied to develop the environmental impact indices for the benchmarking buildings as summarized in Table 5.12.

Table 5.12 Weighting schemes for environmental impact measures

Environmental impact measures	Weighting schemes (w_{mi} %)		
	EPA Science Advisory	BEES Stakeholder Panel	Equal weighting
Global warming potential	25.00	39.19	12.50
Acidification potential	7.81	4.05	12.50
Human health effect	17.19	17.57	12.50
Eutrophication potential	7.81	8.11	12.50
Smog potential	9.38	5.41	12.50
Ozone depletion potential	7.81	2.70	12.50
Fossil fuel consumption	7.81	13.51	12.50
Eco-toxicity effect	17.19	9.46	12.50

The results of LCIA was used to determine the normalized effects of each environmental impact measure on the material production phase ($E_{mi \rightarrow MPP\ of\ A}$), on the construction phase ($E_{mi \rightarrow CP\ of\ A}$), and on overall cradle-to-gate ($E_{mi \rightarrow CTG\ of\ A}$). For example, if there are three case study buildings (Building 1, Building 2, and Building 3), the GWP of these buildings in their material production phase are calculated by performing LCIA and then normalized to determine the corresponding effects on this phase of the buildings (i.e., $E_{GWP \rightarrow MPP\ of\ Building1}$, $E_{GWP \rightarrow MPP\ of\ Building\ 2}$, and $E_{GWP \rightarrow MPP\ of\ Building3}$).

It should be stressed that although the impact measures are cost criteria by nature (i.e., the higher the value of an impact measure, the worse the environmental performance of the building), the impact measures have been considered as the benefit criteria in the proposed framework and the associated equations above. Therefore, this was considered when normalizing the quantities of the impact measures to obtain the normalized effects. For example, a building with higher quantity of an impact measure (e.g., GWP) in its construction phase will contribute to the corresponding environmental impact less than other buildings.

5.3.8 Material Consumption in Construction (MCC)

Efficient consumption of energy, materials, and natural resources are collectively called "resource efficiency" that leads to products and services with less resource consumption and less environmental burdens over the entire life cycle (Ruuska and Häkkinen 2014). The construction industry is amongst the key contributors to resource consumption and the associated environmental impacts. As discussed earlier, the construction industry is the largest consumer of material resources (40- 60% of the total raw material extractions), energy (40% of the total energy consumption) and largest waste to landfills (Bilal et al. 2016; Edwards 2014; Ahn et al. 2009; Achal et al. 2015; Bribian et al. 2011). For example, the building sector is one of the three key sectors in the European Union that needs to improve the resource efficiency since it can influence about 40% of the energy consumption, about 35% the GHG emissions, and over 50% of all extracted materials (European Commission 2011).

Material efficiency, as the wise consumption of materials, is among the most significant resource efficiency strategies in the construction industry that can play roles in different aspects. Material efficiency is effective consumption of natural material resources, reduction of waste, and recycling. In addition to resource depletion due to inefficient material consumption, limited availability of materials can produce negative economic impacts. Furthermore, as discussed in the previous sections, activities related to extraction of primary resources (i.e., raw materials) and the manufacturing of products and processed materials for building construction can be labor and energy intensive, which result in negative economic and environmental impacts. Moreover, material mining and extracting may alternate land use, which has its negative impacts (Ruuska and Häkkinen 2014). Therefore, efficient material consumption in the construction phase of buildings can significantly contribute to sustainability and needs to be considered and addressed earlier in the design stage.

Among the above-mentioned aspects that can be influenced by material efficiency, investigation of the material resource depletion is the main intent of the 'Material consumption in construction (MCC)' SPC. When it comes to quantification of this SPC, the total materials of different kinds consumed in a building including the materials directly used as the processed materials or the materials used in different products of the building should be quantified based on functional unit of the building. In addition, the least and most desirable amount of each material type per functional unit should be established. However, buildings use diverse materials with different weight/volume and corresponding waste percentages. Therefore, it is not an easy task to compare the performance of two buildings (even the same size) from the material consumption point of view. This might be the reason why the studies that have been conducted to address material efficiency did not directly compare the amount of materials used in their case study buildings. As a result, no studies were found that provided the least and most desirable performances for different building material types. Similarly, due to the same reasons, experts were unable to provide such performance benchmarks.

Instead, many studies considered the strategies that can result in less consumption of materials. In this regard, to evaluate material depletion, strategies such as waste prevention, reuse of components, use of renewable and recycled materials, were found more reasonable than direct quantification of the consumed materials. In other words, the more implementation of such strategies, the more resource preservations, regardless of the type of materials. The SPCs correspond to such strategies (i.e., CWM, REP) have already been prioritized in Chapter 4 and then, earlier in this chapter, suitable PLFs were developed for their quantification. Therefore, because 1) The performance benchmarks of this SPI are not available; and 2) Other related SPCs (CWM, REP) sufficiently (and indirectly) addressed the MCC SPC in this research; there is no need to develop a sustainability index for this SPC.

It is worth to mention that, the MCC SPC was initially was selected because different references had emphasized the importance of material consumption in construction of buildings and also because the experts participating in Survey A had rated this SPC as a ‘High’ importance criterion for sustainability assessment of modular buildings. However, similar to other SPCs, the measurability of this SPC had been left for this phase of the research to examine the availability of suitable measurable indicators and corresponding performance benchmarks.

5.4 Economic SPCs

Economic dimension is another key dimension of a sustainable building. Efficient performance of a building with respect to suitable criteria (SPCs) that can sufficiently represent this dimension, can offer significant economic benefits (e.g., added value) or provide ways to avoid unexpected expenses (e.g., repair costs). In this section, similar to what was performed above for the environmental SPCs, an attempt was made to determine appropriate measurement methods that lead to development of sustainability indices for the selected economic SPCs (Table 5.1).

The selected economic SPCs in this research can be classified into two types: direct-impact and indirect-impact. The direct-impact economic SPCs are those that directly deal with costs throughout a building's life cycle and are calculated and expressed in the form of monetary values. Four of the economic SPCs are direct-impact including 'Design and construction costs (DCC)', 'Operational costs (OC)', 'Maintenance costs (MC)', and 'End of life costs (EC)'. Nevertheless, the indirect-impact economic SPCs indirectly deal with the life cycle costs and are not calculated and expressed based on monetary values. The remaining five SPCs are indirect-impact including 'Integrated management (IM)', 'Durability of building (DB)', 'Adaptability of building (AB)', 'Design and construction time', and 'Investment and related risks'.

High locality sensitive SPCs

As discussed in the Methodology section, the information regarding the least and most desirable performance values and corresponding ranges of data variables for the SPIs under some of the economic SPCs can be significantly dissimilar in different regions (locality sensitive SPCs). For example, even though the cities of Vancouver and Kelowna both are located in the same province of BC, the construction costs per functional unit (1 ft^2 of the total area) can be different. Among all the economic SPCs, six SPCs were recognized to be locality sensitive including:

- Design and construction time (DCT);
- Design and construction costs (DCC);
- Operational costs (OC);
- Maintenance costs (MC);
- End of life costs (EC); and
- Investment and related risks (IRR)

In this research, an attempt was made to collect local information to establish suitable PLFs for the determined indicators under each of these SPCs. In this regard, the literature was searched to find information relevant to the Okanagan construction circumstances. In addition, a questionnaire survey, Survey B, was designed and conducted based on the Delphi method to collect the required information related to the single-family residential buildings with the total floor area of less than 3000 ft^2. This total area upper limit was chosen because, based on expert consultations during the design of this survey, residential buildings over 3000 ft^2 are generally custom built with higher quality than typical average-quality single-family houses; therefore, the performance information can be different.

First, a list of experienced design and construction firms whose main expertise lied in design and construction of conventional residential buildings (single-family houses) in the Okanagan, BC, has been complied along with their contact information. Then, they have been contacted via both emails and in-person meetings in their offices to discuss the research, request for participation, and deliver the survey forms. Initially, eleven construction firms showed interest in the research. However, when they were informed about the data collection methodology and requirement for follow up meetings (Delphi method), six firms withdrew from participation and the remaining five firms continued their participation in the research. In two of the participating firms, a group of experts completed one questionnaire as the representative of their collective opinions. In addition, one independent expert who had been involved in different building projects in the Okanagan, joint the research. Therefore, in total, six questionnaire forms were completed during the course of survey administration. In addition to the participating experts, two additional experts who did not have time to participate in all steps of the survey provided their opinions within a single interview.

The expertise of the participating firms lied in different aspects of residential buildings. For example, one of the firms was specialized mainly in the design not construction, even though the corresponding expert was knowledgeable about the economic data of construction. The other firms were specialized mainly in construction; however, they well knew the design costs since they have been dealing with the design phase of their projects. Furthermore, four of the experts were also presidents of their firms, which means they had access to all information required to complete the survey. The professional experience of the experts from the participating firms ranged from 6 to 40 years with the average of 23 years. Despite limited number of experts, their comprehensive experience and also their involvement in diverse residential building projects in the Okanagan ensured the validity of the collected data.

Depending on the desire and schedule of the participants, the data was collected in each round using a combination of different methods including asking the survey questions through individual interviews, phone calls (Keil et al. 2013), or delivering the survey forms and collecting the completed forms after a few days (Pirdashti et al. 2011; Juwana et al. 2010). In the first round of data collection, the required information was explained to the experts, the questionnaire forms were delivered, and if requested, they were given a few days to provide their answers. Subsequently, the collected data was reviewed by the survey administrator to recognize and list possible ambiguous answers that needed clarifications. For example, while the cost data was required to be provided per 1 ft^2 as a functional unit of single-family residential buildings, some of the participants provided the total cost without mentioning the total floor area of the building they referred to. Therefore, the corresponding participants were contacted to clarify such answers before including them in the pool of answers. Subsequently, the answers provided by experts ware averaged as the new answers. In the second round, the experts were provided with these new answers and asked to review and, if required, revise/modify them. The same method was followed until the third round where the consensus was reached on all the answers. Consequently, the results of Survey B were used to establish the PLFs for the SPIs associated with the above listed SPCs. It should be mentioned that, within the same survey (Survey B), the participants were asked a number of additional questions related to the next phases of this research that have been explained in the next chapter.

Less locality sensitive SPCs

Despite the above-mentioned SPCs, the least/most desirable performances of buildings with respect to other economic SPCs including ‘Integrated management (IM)’, ‘Durability of building (DB)’; and ‘Adaptability of building (AB)’ are approximately similar throughout BC. For these SPCs, the same process that has been performed earlier in this chapter to establish the PLFs for the environmental SPCs was used. Therefore, first, relevant measurable indicators (SPIs and sub-SPIs) along with their relative importance weights were determined. Then, for each indicator, the least and most desirable performance values and corresponding ranges of data variables have been established. In this regard, different sources including rating systems and published articles and reports were reviewed. In addition, experienced experts in the construction industry were consulted. Subsequently, a PLF has been established for each indicator by which the performance of the subject building with respect to that indicator can be calculated and presented with a PL between 0 and 100.

Except only one SPC (i.e., EC), this research successfully determined suitable indicators under each economic SPC and established the corresponding PLFs. In total, 37 indicators were determined under the economic SPCs including 17 SPIs and 20 sub-SPIs as summarized in Table 5.13. The table also lists the sources used to identify the measurement method of an indicator and subsequently to establish the corresponding PLF. Details are provided in the following sections.

Table 5.13 Economic SPCs and corresponding indicators

SPIs	sub-SPIs	Sources
	Integrated management (IM)	
IM1 Integrated design processes	IM1-1 Pre-design meetings	BREEAM, Green Globes, EO
	IM1-2 Performance goals	BREEAM, Green Globes, EO
	IM1-3 Progress meetings	BREEAM, Green Globes, EO
IM2 Life cycle cost	IM2-1 Elemental life cycle cost	BREEAM, EO
	IM2-2 Component level life cycle cost	BREEAM, EO
IM3 Commissioning	IM3-1 Commissioning schedule and responsibilities	BREEAM, Green Globes, EO
	IM3-2 Whole building commissioning	BREEAM, Green Globes, EO
	IM3-3 Training and handover	LEED, BREEAM, EO
	Durability of building (DB)	
DB1 Roofing and openings	DB1-1 Roofing membrane assemblies	Lit., Green Globes
	DB1-2 Envelope flashings	Lit., Green Globes
	DB1-3 Roof and wall openings	Lit., Green Globes
DB2 Foundation waterproofing		Lit., Green Globes
DB4 Barriers	DB4-1 Air barriers	Lit., Green Globes
	DB4-2 Vapor retarders	Lit., Green Globes
DB3 Cladding	DB3-1 Exterior wall cladding systems	Lit., Green Globes
	DB3-2 Rain screen wall cladding	Lit., Green Globes
	Adaptability of building (AB)	
AB1 Expandability	AB1-1 Lateral expandability	Lit., EO
	AB1-2 Vertical expandability	Lit., EO
AB2 Dismantlability		Lit., EO
AB3 Record keeping		Lit., EO
	Design and construction time (DCT)	
DCT1 Design time		Lit., EO
DCT2 Construction time		Lit., EO
	Design and construction costs (DCC)	
DCC1 Design cost		Lit., EO
DCC2 Construction cost		Lit., EO
	Operational costs (OC)	
OC1 Running costs		Lit., EO
	Maintenance costs (MC)	
MC1 Repair and replacement costs		Lit., EO
	Investment and related risks (IRR)	
IRR1 Return on investment	IRR1-1 Sale price	Lit., EO
	IRR1-2 Design cost	Lit., EO
	IRR1-3 Construction cost	Lit., EO

Note: Lit. = literature; LEED = Leadership in Energy and Environmental Design; BREEAM = Building Research Establishment Environmental Assessment Method; EO = expert opinions.

5.4.1 Integrated Management (IM)

Integrated management (IM) during the design and construction of a building can effectively help the project's economic performance. The IM SPC encourages sustainable management practices with respect to design, construction, commissioning, and handover of a building by setting and implementing suitable sustainability objectives to avoid extra costs later in the use phase of the building. This SPC consists of three SPIs: 'IM1 Integrated design processes', 'IM2 Life cycle cost', and 'IM3 Commissioning'. Each of these SPIs comprises a number of sub-SPIs as demonstrated in Figure 5.10.

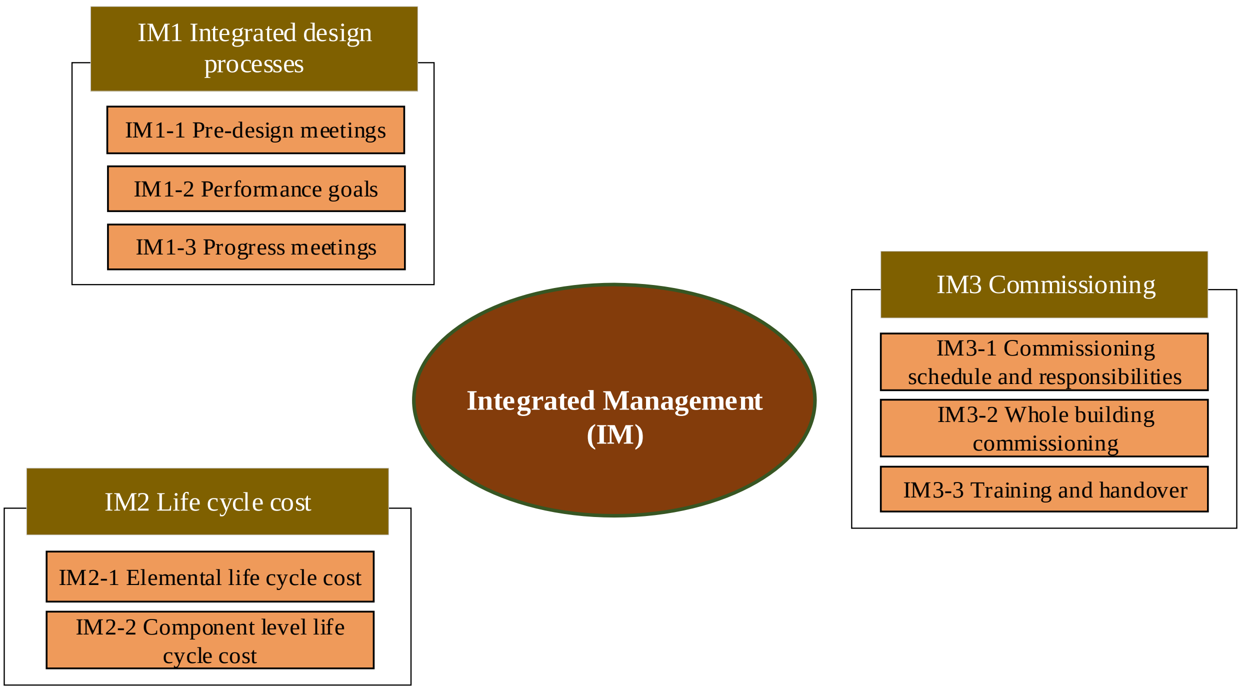

Figure 5.10 SPIs and sub-SPIs associated with 'Integrated management'

5.4.1.1 Integrated design processes (IM1)

The aim of this SPI is to ensure that the environmental and functional objectives of the building are satisfied in a cost-efficient manner through the cooperation of different disciplines involved in the project. In other words, it looks for an integrated design process that enhances the building performance (BRE 2016). This SPI is split into three sub-SPIs: 'IM1-1 Pre-design meetings', 'IM1-2 Performance goals', and 'IM1-3 Progress meetings' (GBI 2014; GBI 2015; BRE 2016).

Pre-design meetings (IM1-1)

A significant factor that influences the design and construction of a sustainable building that can also meet the needs of the end-users (clients) is to establish all goals at the beginning of the design process. In addition, involvement of the project team members throughout the project is another significant factor. In other words, the project team should know the established basic goals and the associated criteria and also the responsibility of each member for ensuring that each criterion is successfully addressed.

To this end, attendance of the representatives of main design disciplines in pre-design planning sessions is important. Such sessions can be in the form of one or more “all hands” project meetings, design charrettes, or workshops during pre-design of the project. The number of such meetings in a project depends on size and complexity of the building as well as the desired sustainability goals. For example, a minimum seven meetings or workshops is recommended by the Whole Systems Integrated Process Guide, while ASHRAE does not mention a required meeting number but emphasizes that the project team should use a charrette process to determine the optimal building arrangement. Regardless of meetings number, this is vital that all key project team members arrange and hold collaborative meetings earlier in the design stage and continue through the use phase of the building.

The performance of a building project with respect to this sub-SPI is evaluated according to the involvement of the following key design disciplines and stakeholders in collaborative meetings during the design stage (GBI 2015):

- Owner’s representative
- Architect
- Green building expert or sustainable design coordinator
- Civil engineer
- Electrical engineer
- Mechanical engineer – HVAC
- Structural engineer

Consequently, the PLF below can be used to calculate the performance level of IM1-1:

$$PL_{IM1\text{-}1} = 25n \qquad n = 0, 1, .., 4 \qquad [5.89]$$

Where n is the number of key disciplines involved in “all hands” project meetings, design charrettes, or workshops.

Performance goals (IM1-2)

This sub-SPI considers the establishment of qualitative design goals and performance metrics. The project team should review the applicable sustainability criteria available in the literature such as rating systems or other standards. Subsequently, during “all hands” meetings or design charrettes, the project designers should identify the performance standards and the corresponding indicators by which the project success can be evaluated.

The performance levels of this sub-SPI is identified based on establishment of qualitative design goals and performance metrics for any or all of the following items:

- Site design
- Envelope
- Materials efficiency
- Indoor environment
- Energy efficiency
- Renewable energy (percentage of total energy)
- Greenhouse gas emissions and life cycle impact
- Water conservation, efficiency, and reuse
- Construction waste management

The performance level of this sub-SPI can be calculated using the following PLF:

$$PL_{IM1\text{-}2} = 16.67n \qquad n = 0, 1, .., 6 \qquad [5.90]$$

Where n is the number of items whose qualitative green design goals and quantitative performance metrics have been established at the pre-design stage.

Progress meetings (IM1-3)

The intent of holding progress meetings throughout the design process by all the project stakeholders is to review performance goals and modify them if necessary, refine language regarding performance goals outcomes into plans and specifications, realize and correct possible missing requirements, and define and track the responsibilities.

The performance level of this sub-SPI is calculated according to holding progress meetings before completion of each of the following design stages:

a- Concept design stage: Where the general scope, initial design, and the relationships between various components are defined. In addition, the cost and timeline are established.

b- Design development stage: Where detailed plans and drawings that show the main elements such as electrical, mechanical, structural, plumbing systems, and so forth, are produced.

c- Construction documents stage: Where the finalized drawings that show detailed specifications of all systems and components are generated.

Subsequently, the following PLF can be used to measure the sub-SPI IM1-3:

$$PL_{IM1\text{-}3} = 33.33n \qquad n = 0, 1, 2, 3 \qquad [5.91]$$

Where n is the number of the project design stages listed above for which progress meetings have been held prior to their completion.

Eventually, the PL of the parent SPI is calculated by aggregating the PLs of all three associated sub-SPIs and their relative importance relationships as:

$$PL_{IM1} = 0.25 \times PL_{IM1\text{-}1} + 0.5 \times PL_{IM1\text{-}2} + 0.25 \times PL_{IM1\text{-}3} \qquad [5.92]$$

5.4.1.2 Life cycle cost (IM2)

The IM2 SPI seeks enhancing economic sustainability by using life cycle cost (LCC) analysis at the design stage of a building (BRE 2016). LCC considers the whole life cycle costs from the design to the end of life to ensure that the systems and specifications designed are based on the lowest costs and highest value for money. This SPI comprises two sub-SPIs ‘IM2-1 Elemental life cycle cost’ and ‘IM2-2 Component level life cycle cost’ (BRE 2016). By implementing these sub-SPIs, different alternative systems, elements, and component, can be compared and appraised to optimize the life cycle cost plan.

Elemental life cycle cost (IM2-1)

The LCC models can be used to perform a whole building elemental life cycle cost analysis at the concept design stage. The outcomes provide a prediction of cash flow for the whole building. The elemental LCC models can include (BRE 2016):

- Construction costs including initial capital expenditure, other construction related costs, and client definable costs.
- Maintenance costs including major and minor replacement and repairs, allowances for unscheduled repairs.
- Operational costs including fuel, water and drainage, rates, and other local charges.
- End of life costs including deconstruction, demolition, recycling, landfilling.

The performance level of the subject building with respect to the IM2-1 sub-SPI is assigned based on meeting the conditions outlined below:

a- Conducting an elemental LCC (such as construction costs, maintenance costs, operational costs) at the concept design stage together with any design option appraisals.

b- If the elemental LCC was performed, does it predict the future replacement costs at particular time from the start of the use phase required by the client such as 20, 40, or 50 years?

c- If the elemental LCC plan was performed, does it provide maintenance and operational cost estimates?

d- Was it demonstrated, using appropriate examples provided by the analysis team that how the results of the performed elemental LCC was utilized to modify the design of systems and specification to minimize the life cycle costs?

The performance level of IM2-1 can be measured by the following PLF:

$$PL_{IM2\text{-}1} = 25n + 25nm \qquad n = 0, 1;\ m = 0, 1, 2, 3 \qquad [5.93]$$

Where n is 1 if the condition 'a' was met and m is the number of conditions 'b', 'c', and 'd' that were met.

Component level life cycle cost (IM2-2)

This sub-SPI considers the component level LCC that are performed by the end of the design development stage. The main component types to perform LCC options appraisal include (BRE 2016):

- Envelope, such as roofing, windows, and cladding.
- Services such as heating, cooling, and controls.
- Finishes such as floors, walls, and ceilings.
- External spaces such as alternative hard landscaping and boundary protection

Figure 5.11 illustrates an example for the cost of two cooling systems over 60 years (in real discounted costs).

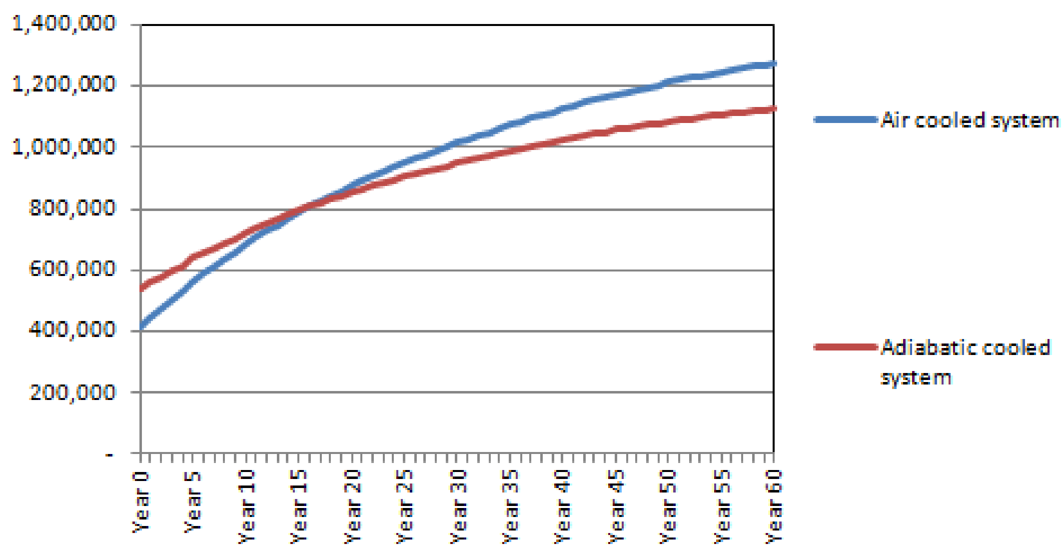

Figure 5.11 Costs of two systems of cooling over 60 years of building life span

The performance level for the IM2 sub-SPI is calculated according to performing a component level LCC options appraisal for any of the aforementioned component types as:

$$PL_{IM2\text{-}2} = 20n + 20m \qquad n = 0, 1, .., 4;\ m = 0, 1 \qquad [5.94]$$

Where *n* is the number of component types that LCC were performed for, and *m* is 1 if the design team demonstrated, using appropriate examples, that how the results of the component level LCC used to modify the designed systems and specification to minimize the life cycle costs.

When the PLs of the two sub-SPIs are obtained, the PL of the corresponding IM2 SPI is obtained using the function below:

$$PL_{IM2} = 0.67 \times PL_{IM2\text{-}1} + 0.33 \times PL_{IM2\text{-}2} \qquad [5.95]$$

5.4.1.3 Commissioning (IM3)

This SPI encourages the design, construction, and calibration of the building systems in a way that they operate as intended (GBI 2015) and reflect the needs of the building occupants (BRE 2016). The SPI consists of three sub-SPIs: 'IM3-1 Commissioning schedule and responsibilities', 'IM3-2 Whole building commissioning', and 'IM3-3 Training and handover' (BRE 2016).

Commissioning schedule and responsibilities (IM3-1)

Commissioning and testing are performed by the main contractor/builder of a building according to a schedule that has been established in the design phase. Such schedule specifies the standards that all commissioning activities are performed based on, such as national best practice commissioning codes or any other accepted standards (where applicable). The schedule includes a timeline for commissioning and recommissioning activities regarding services and control systems and also testing and inspecting the fabric (e.g., roof, floors, columns, walls, windows, and doors).

The performance level of the IM3-1 sub-SPI is calculated based on meeting the following:

a- Is there a schedule of commissioning and testing that specifies all the activities required by the standards such as national best practice commissioning codes or any other suitable standards?

b- Is an individual from the project team chosen to monitor and program the pre-commissioning, commissioning, and testing activities?

The PLF for this sub-SPI is:

$$PL_{IM3\text{-}1} = 50n \qquad n = 0, 1, 2 \qquad [5.96]$$

Where *n* is the number of conditions 'a' and 'b' that was met.

Whole building commissioning (IM3-2)

The integrity and quality of the building envelope and systems is ensured by completion of pre-commissioning, commissioning, testing, and inspection activities in accordance with the schedule outlined above.

The performance of this sub-SPI is measured based on commissioning the following envelope and systems of the building at the pre-design, design, and construction stages (BRE 2016):

C1- HVAC and refrigeration systems and their controls;
C2- Building envelope (roofing assemblies, windows and doors, waterproofing assemblies, and cladding/skin);
C3- Structural systems;
C4- Fire protection system;
C5- Plumbing system;
C6- Electrical system; and
C7- Lighting system and their controls.

The following PLF can be used to calculate the IM3-2 sub-SPI:

$$PL_{IM3\text{-}2} = \{Max\ (25n + 12.5m), 100\} \quad n = 0, 1, 2;\ m = 0, 1, 2, .., 5 \qquad [5.97]$$

Where *n* is the number of the building envelope and systems 'C1' and 'C2', and *m* is the number of the building envelope and systems 'C3' to 'C7' that have been commissioned.

Training and handover (IM3-3)

Building end users (occupants) should know how to use the building's systems and equipment such that they operate in an effective manner as intended. The performance of a building with regard to this sub-SPI is measured based on meeting the following conditions (BRE 2016):

a- Before handover of the building, a building or home user guide is developed and delivered to the end user(s).

b- Around handover of the building, a training session is schedule that includes the items below:

- The building's design objectives;

- The aftercare activities by the builder/contractor such as any scheduled seasonal commissioning and post occupancy testing;

- Explanation and description of installed systems and key features, controls and their interface, to end user(s);

- Explanation of the developed user guide and other relevant building documentation; and

- Maintenance information and requirements of the building.

The following PLF can be used to measure the performance of this sub-SPI:

$$PL_{IM3\text{-}3} = 50n + 10m \qquad n = 0, 1;\ m = 1, 2, .., 5 \qquad [5.98]$$

Where n is 1 if the condition 'a' was met and m is the number of items under condition 'b' that were met.

Finally, the PL of the IM3 SPI is calculated by combining the PLs of the three sub-SPIs as:

$$PL_{IM3} = 0.25 \times PL_{IM3\text{-}1} + 0.5 \times PL_{IM3\text{-}2} + 0.25 \times PL_{IM3\text{-}3} \qquad [5.99]$$

5.4.1.4 Relative importance of the SPIs under IM

To calculate the sustainability index for the IM SPC, both the PLs of the associated SPIs and their importance weights are required. According to the BREEAM rating system, the weights of the IM1, IM2, and IM3 SPIs came to be 0.364, 0.272, and 0.364, respectively (BRE 2016).

5.4.2 Durability of Building (DB)

Durability is another indirect-impact criterion that can influence the economic performance of buildings. Durability is a building capability to perform its intended function during the use phase with minimal unexpected requirements for repair or maintenance expenses (CaGBC 2009). The quality of materials and products used in a building along with the quality of construction and installation (off-site and on-site) activities play a significant role in the overall durability of the building. In a durable building, suitable design and specification measures are considered such that the degradation of materials and components during the lifetime of the building and the subsequent replacements and repairs are minimized (ILFI 2014; BRE 2016).

To this end, the 'Durability of building (DB)' is a SPC that considers the incorporation of measures for adequate protection of exposed elements and landscape of a building to prolong its life; thus, reduce economic impacts associated with damage and wear and tear. The DB SPC comprises four SPIs some of which include a number of sub-SPIs as illustrated in Figure 5.12.

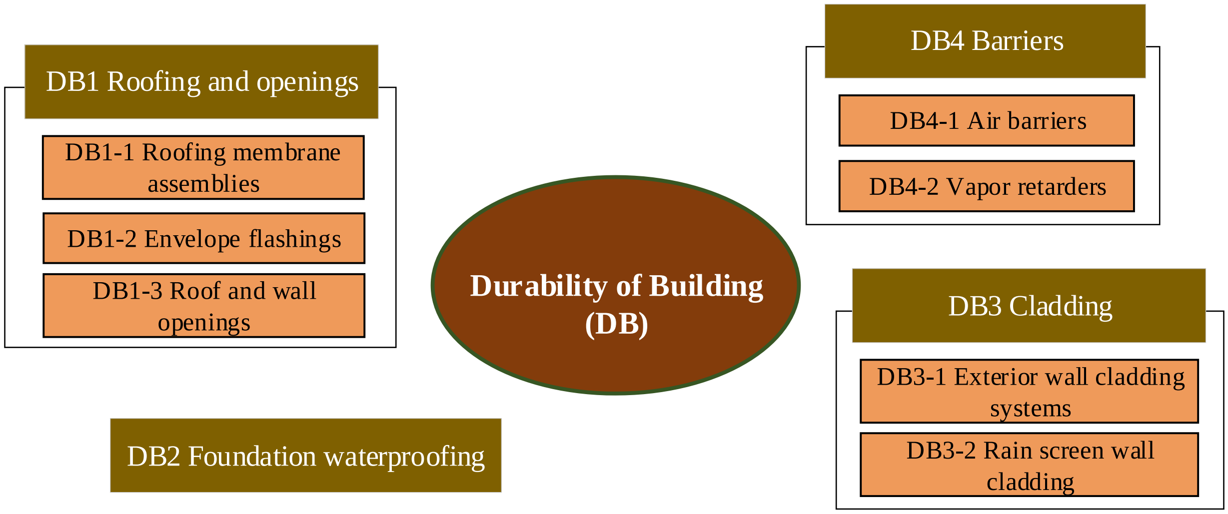

Figure 5.12 SPIs and sub-SPIs associated with 'Durability of building'

5.4.2.1 Roofing and openings (DB1)

The aim of this SPI is to implement roofing/opening design measures to enhance the performance and durability. This indicator comprises three sub-SPIs: 'DB1-1 Roofing membrane assemblies', 'DB1-2 Envelope flashings', and 'DB1-3 Roof and wall openings' (GBI 2015).

Roofing membrane assemblies (DB1-1)

The performance of the subject building with respect to this sub-SPI is evaluated based on implementation of the following items:

a- Roofing membrane assemblies and systems should be installed in accordance with the instructions by the corresponding manufacturers.

b- The installed roofing membrane assemblies and systems should be inspected by professionals by the manufacturers or a third-party roofing expert.

The performance level of DB1-1 is calculated as:

$$PL_{DB1\text{-}1} = 50n \qquad n = 0, 1, 2 \qquad [5.100]$$

Where n is the number of items listed above that have been implemented while constructing and commissioning the roof assemblies of the subject building.

Envelope flashings (DB1-2)

Flashings and sheet metals act as a defense line to protect a building envelope against moisture. This sub-SPI ensures the quality installation of the envelope flashing by checking the items below (GBI 2015):

a- Envelope flashings and sheet metal assemblies should be installed in accordance with the instructions by the industry best practices.

b- The installed envelope flashings and sheet metal assemblies should be inspected as per prescribed industry protocol or by a third-party expert.

Consequently, the PLF below can be used to calculate the performance level of DB1-2:

$$PL_{DB1\text{-}2} = 50m \qquad m = 0, 1, 2 \qquad [5.101]$$

Where m is the number of implemented items 'a' and 'b'.

Roof and wall openings (DB1-3)

To ensure the quality of the products correspond to a buildings' roof and windows openings, the following conditions should be examined (GBI 2015):

a- All products associated with wall and roof openings such as windows and doors, should include moisture management designs.

b- These products should inspected against water penetration in accordance with industry best practices.

Subsequently, the following PLF can be used to measure the DB1-3 sub-SPI:

$$PL_{DB1\text{-}3} = 50k \qquad k = 0, 1, 2 \qquad [5.102]$$

Where k is the number of conditions 'a' and 'b' that have been satisfied.

When all the three sub-SPIs have been calculated, the parent DB1 SPI is calculated by aggregating the calculated PLs and their weights as:

$$PL_{DB1} = 0.3 \times PL_{DB1\text{-}1} + 0.3 \times PL_{DB1\text{-}2} + 0.4 \times PL_{DB1\text{-}3} \qquad [5.103]$$

5.4.2.2 Foundation waterproofing (DB2)

The intent of this indicator is to investigate if the foundation waterproofing design measures have been implemented to enhance the durability of the foundation; hence, the whole building. The performance is evaluated cumulatively using the following measures (GBI 2015):

a- Newly installed foundation systems for conditioned spaces are constructed with slab-on-ground vapor retarders in accordance with industry best practices.

b- Newly installed foundation systems for conditioned spaces are constructed such that all slabs on grade will be positioned directly over vapor retarders and capillary-break base courses.

c- The installed foundations should be field-inspected conforming to industry protocol.

It is important to note that, in addition to the above stated foundation waterproofing measures, the literature provided more measures. However, they have not mentioned in this study because either they were irrelevant to residential buildings or, according to experts, they were not applicable to the construction circumstances in BC.

Subsequently, the following PLF can be used to calculate the performance level of the DB2 SPI:

$$PL_{DB2} = 25m + 50n \qquad m = 0, 1, 2;\ n = 0, 1 \qquad [5.104]$$

Where m is the number of measures 'a' and 'b' that have been implemented and n is 1 if measure 'c' was met.

5.4.2.3 Cladding (DB3)

Cladding is the application of a layer of non-structural material (cladding) over the layer of another material (usually the load bearing materials). The primary purpose of cladding is to enhance the aesthetics of a building's walls. However, it also offers resistance and protection leading to enhanced durability of structural materials (Jacobs 2017). The aim of the DB3 SPI is to examine the implementation of adequate cladding measures. This SPI included two sub-SPIs: 'DB3-1 Exterior wall cladding systems' and 'DB3-2 Rain screen wall cladding' (GBI 2015).

Exterior wall cladding systems (DB3-1)

The sub-SPI is measured based on the following measures (GBI 2015):

a- Has one of the following cladding systems been installed as per industry best practices?

- Install Exterior Insulation Finishing Systems (EIFS) as water-managed systems conforming to the instructions by the corresponding manufacturers.
- Install masonry veneer cladding conforming to industry technical instructions.
- Install aluminum framed glazing systems conforming to the instructions by the manufacturers. The systems should be warranted by the corresponding manufacturers.

b- If the answer to measure 'a' is YES, has the installed cladding system been inspected as per the appropriate prescribed industry protocols?

c- Have joint sealers been installed and field-inspected in accordance with industry best practice?

The performance of the subject building with respect to DB3-1 is calculated as:

$$PL_{DB3\text{-}1} = 33.3n \qquad n = 0, 1, 2, 3 \qquad [5.105]$$

Where n is the number of above states measures that have been satisfied when implementation of the eexterior wall cladding.

Rain screen wall cladding (DB3-2)

The performance level of this sub-SPI is measured using the following measures (GBI 2015):

a- Do the construction documents indicate that exterior rain screen wall cladding systems specified over framed walls are to be installed with the following items?

- Primary and secondary line of defense.
- An air barrier.
- A means for incidental bulk water intrusion to escape the cladding system assembly.

b- Are the rain screen cladding assemblies installed in accordance with AAMA 508-07 laboratory testing requirements or any other accepted standard?

The PLF for this sub-SPI was established as:

$$PL_{DB3\text{-}2} = 25k + 25l \qquad k = 0, 1, 2, 3; l = 0, 1 \qquad [5.106]$$

Where k is the number of implemented items listed under measure 'a' and l is 1 if measure 'b' has been met.

Once the PLs of the two sub-SPIs are obtained, the PL of the DB3 SPI can be calculated as:

$$PL_{DB3} = 0.6 \times PL_{DB3\text{-}1} + 0.4 \times PL_{DB3\text{-}2} \qquad [5.107]$$

5.4.2.4 Barriers (DB4)

This indicator appraises the quality implementation of barrier design measures, which can lead to enhanced durability of the subject building. The DB4 SPI includes two sub-SPIs: 'DB4-1 Air barriers' and 'DB4-2 Vapor retarders' (GBI 2015).

Air barriers (DB4-1)

Air barriers are used to decrease the uncontrolled air movement from the envelope. The performance of a building with respect to this sub-SPI is assessed according to the following measures (GBI 2015):

a- If installation of a continuous air barrier has been incorporated in the design stage, indicate of any of the following practices have been considered:

- An airtight and flexible joint between the air barrier material and adjacent assemblies.
- The designed air barrier is able to withstand combined design winds (negative and positive), stack and fan pressures without displacement or damage.
- The designed air barrier is able to withstand structural movement and also no displacement due to full load.

- Connection details of the air barrier between different assemblies and components, such as foundation and walls, wall and roof, walls and windows, and so forth, are available in the construction documents.

b- Is the designed continuous air barrier for the opaque building envelope in accordance with the relevant local building code or either of the following standards?

- ASTM E2178-11 Standard Test Method for material testing;
- ASTM E2357-11 Standard Test Method for assembly testing;
- ASTM E779-03 or equivalent method for building testing.

Consequently, the PLF below has been established to calculate DB4-1:

$$PL_{DB4\text{-}1} = 12.5i + 50j \qquad i = 0, 1, 2, 3, 4;\ j = 0, 1 \qquad [5.108]$$

Where i is the number of practices listed under measure ‘a’ that have been implemented and j is 1 if any of the standards mentioned under measure ‘b’ was followed.

Vapor retarders (DB4-2)

Uncontrolled moisture in the indoor air of a building can result in serious problems. If such moisture enters the ceiling or walls, it can create a suitable environment for the mold and mildew growth, which results in health issues, degradation of the building’s structural integrity, damage of the materials, and negative impacts on the thermal efficiency and indoor air quality (Al-Homoud 2005). To minimize the moisture (i.e., movement of water due to vapor diffusion), vapor retarders are utilized. Vapor retarders are elements made by special materials such as treated papers, plastic sheets, among others, that are designed and installed in assemblies of a building to retard the passage of water vapor (Al-Homoud 2005; Lstiburek 2004).

The DB4-2 sub-SPI is evaluated using the following measures (GBI 2015):

a- Install the interior side of framed walls with a Class I or II vapor retarder conforming to the relevant local building code or (in absence) and an accepted international code such as Energy Conservation Code 2012.

b- Install on the walls of unvented crawl spaces insulation that is permanently fastened to the walls and extends downward from the floor to the finished grade level, and then vertically and/or horizontally for at least an additional 60 cm.

c- Use a continuous Class I vapor retarder to cover exposed earth in unvented crawl space foundations and implement the items below:

- all joints of the vapor retarder are overlapped by 15 cm and are sealed or taped; and

- the edges of the vapor retarder extend at least 15 cm up the stem wall and are attached to the stem wall.

Consequently, the PLF below can be used to calculate the performance level of DB4-2:

$$PL_{DB4\text{-}2} = 33.3n \qquad m = 0, 1, 2, 3 \qquad [5.109]$$

Where n is the number of vapor retarder measures ‘a’, ‘b’, and ‘c’ that have been implemented.

Once the PLs of these two sub-SPIs have been calculated, the PL of the corresponding SPI is measured using the equation below:

$$PL_{DB4} = 0.571 \times PL_{DB4\text{-}1} + 0.429 \times PL_{DB4\text{-}2} \qquad [5.110]$$

5.4.2.5 Relative importance of the SPIs under DB

According to the scoring system provided by Green Globes (GBI 2015), the weights of DB1, DB2, DB3, and DB4, were determined as 0.417, 0.083, 0.208, and 0.292, respectively. These weights and the calculated PLs are used to develop a sustainability index for the DB SPC.

5.4.3 Adaptability of Building (AB)

Buildings, as a significant share of the built environment, are built mainly to meet the society and people’s requirements. It is possible that these requirements change during the use phase of buildings (Fernandez 2003; Moffatt and Russell 2001). Buildings should be able to sufficiently respond the changes such as needs of owners/users, legislative requirements, new technical and functional technologies, and so forth (Mansfield 2009; Manewa et al. 2016; Fernandez 2003; Greden 2005). According to Energy Research Group (1999), any underperforming building with respect to comfort conditions, energy efficiency, or environmental impact can be a potential nominee for adaptation. Therefore, it is important to consider such possible changes in the design and construction of buildings (Heidrich et al. 2017).

Adaptability refers to the capability of accommodating minor and major changes in a building (Grammenos and Russell 1997). In other words, adaptable buildings are designed at the design and construction phase of the life cycle in a way that they can accommodate future changes as easy as possible and at lowest costs to meet the evolving user needs as well as statutory requirements (Edmonds and Gorgolewski 2000).

According to Douglas (2006), adaptation and maintenance are classified as the two primary elements of building performance management. Based on this classification, adaptation is interpreted as performance adjustment that leads to optimum performance or maximum standard. On the contrary, since the performance of every building decreases over time, maintenance is interpreted as performance upkeep (i.e., preserve) that returns the performance to its original condition (i.e., early days of the use phase). The economic life of a building can be extended by performing both adaptation and maintenance rather than only maintenance. In addition, the cycles of these two major forms of intervention are different for residential and commercial buildings, which is much shorter in the case of commercial buildings. Residential buildings, such as single-family and multi-family, have a relatively long lifespan with few major interventions (i.e. adaptations) during their use phase.

The SPC 'Adaptability of building (AB)' recognises and encourages measures to accommodate possible changes in the occupancy phase and even in the end of life phase of buildings. However, not all the adaptability strategies are applicable for every building project since each project has its unique circumstances; therefore, a limited number of strategies can represent the level of adaptability of a building (Estaji 2017). For example, convertibility (i.e., allowing for changes in the building main use) has been introduced as one of the important contributors to adaptability (Douglas 2006). However, it is not a common practice to convert a residential dwelling to a commercial building because of the rigidity of the structures and layouts (Moffatt and Russell 2001). Thus, in this research, only those changes and corresponding adaptability strategies that are common and most relevant to residential buildings have been considered when determining suitable indicators under the AB SPC.

It is important to mention that, ideally, suitable indicators (i.e., adaptability measures and strategies) and standardized assessment methods are required by which the level of adaptability in a building can be rated. However, the lack of specific methods and indicators in the literature makes it difficult to measure adaptability of residential buildings and create benchmarks for comparison purposes. This study attempted to initiate the establishment of a baseline for suitable indicators under this SPC and corresponding benchmarks by rationally reviewing and summarizing the information available in the literature and expert feedback. The main reviewed documents included Heidrich et al. 2017; Gosling et al. 2008; Moffatt and Russell 2001; Sumer 1997; CMHC 2004; Greden 2005; Israelsson and Hansson 2009; Estaji 2017; Douglas 2006; Fernandez 2003; Mansfield 2009; Manewa et al. 2016; Energy Research Group (1999), Heidrich et al. 2017; Grammenos and Russell (1997) and Edmonds and Gorgolewski (2000).

Eventually, the total number of three SPIs were determined under the AB SPC as the most relevant adaptability strategies for residential buildings as shown in Figure 5.13. However, the proposed SPIs and associated measures can be modified/revised in the future to represent the most relevant adaptability performance indicators for residential buildings. It is also worth to mention that this SPC examined potential adaptability of buildings; however, since each building is unique and the level of adaptation can be completely different, depending on circumstances and needs, a detailed feasibility study is required before implementation of actual adaptations.

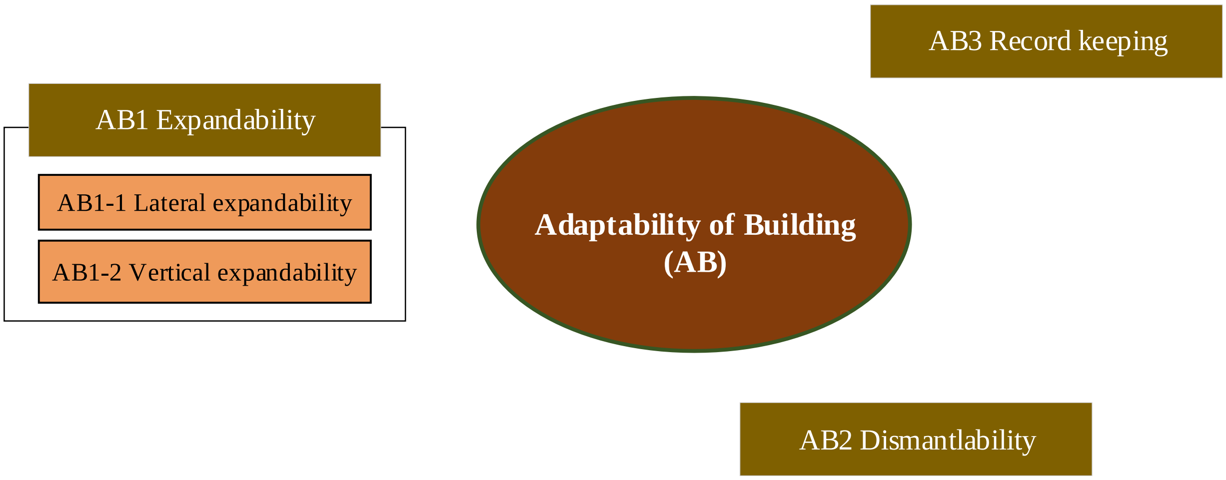

Figure 5.13 SPIs and sub-SPIs associated with 'Adaptability of building'

5.4.3.1 Expandability (AB1)

Expandability means allowing for increases in volume or capacity of a building to accommodate new needs of end users. As stated earlier, conversions to other uses (e.g., residential to commercial) are not common. However, conversions to the same use by expanding or re-configuring the building space is not uncommon. This kind of conversion might require substantial changes in internal parts of the building. For example, converting a building unit into two smaller units requires the design and installation of additional separating walls and floors.

In general, two forms of expansions are performed within same-use conversions: lateral and vertical. The former form is more common and practical than the latter form. The AB1 SPI consists of two sub-SPIs: 'AB1-1 Lateral expandability' and 'AB1-2 Vertical expandability'.

Lateral expandability (AB1-1)

Increasing the spatial capacity of a building is one of the most visible forms of adaptation. This form of adaptation is implemented by adding a horizontal space to the existing building, which can provide facilities that are not existent in the building or provide additional space for accommodation. Another reason for lateral expansion is that it is an effective solution to re-configure and rearrange the existing space in order to accommodate the new living patterns. Examples of lateral expansion are creating facilities such as granny flats or study rooms by extending or re-configuring the existing building.

In addition to responding the evolving needs of the occupants, expansions can increase the property values, which is a significant factor for this form of adaptation. Furthermore, expensive process of moving elsewhere to a larger property (i.e., economic impact) and the associated stressful activities and emotional subsequences (i.e., social impacts) can convince house owners to extend their property rather than relocating.

To evaluate a building's performance with respect to this sub-SPI the inclusion of provisions for future lateral expansions at the design stage is examined by the following measures:

- The building is located and oriented in a way that there is sufficient space around all or part of it for horizontal extensions.

- There are means of access and exit regarding the site and building during the lateral extension activities in order to make less interruption to the surroundings people (e.g., noise, dust).

- Lateral expansions do not disturb the neighborhood access to light, view, and so forth.

- The connections between materials and components facilitate disassembly required for extensions or re-configurations of the space (e.g., prefabricated components, bolted connections).

- Substructure (foundation) has been adequately over-designed to accommodate additional loads due to lateral expansion.

Three possibilities have been considered when evaluating each of the measures above including:

- The measure has not been incorporated in the design stage;
- The measure has moderately been incorporated; or
- The measure has highly been incorporated.

For example, it is likely that the foundation of the given building was over-designed in such a level that allows only small to medium extensions or re-configurations which means that the associated measure was moderately met. Subsequently, the PLF below was established to calculate the PL of this sub-SPI:

$$PL_{AB1\text{-}1} = 25i + 12.5j \qquad i \text{ and } j = 0, 1, 2, 3, 4 \qquad [5.111]$$

Where *i* and *j* are the number of the above lateral expandability measures that have been highly and moderately incorporated in the design of the building, respectively.

Vertical expandability (AB1-2)

Vertical expansions are less common and more expensive than lateral expansions because it is more complicated. For example, vertical expansion needs staircases (to facilitate access to the new accommodation) and creating new roof openings or separating floor to provide access between the old and new sections. This reduces slightly the usable space on the floor immediately below the new level. Building services can be affected by this form of adaptation, in particular, when the added space requires separate bathroom and/or toilet facilities. Furthermore, in some cases, there are requirements to strengthen the existing structure. Moreover, the design of the building foundation should be over-designed such to ensure its strength to bear the added vertical facilities (e.g., new story). However, the foundation of buildings is mostly over-designed and fewer buildings require such substructure strengthening.

Typically, there are two forms of vertical adaptation including roof expansions and basement expansions. The following are possible types of upward and downward vertical expansions or conversions:

- New basement
- Creation of recess area at front and/or rear to permit daylight and ventilation.
- New mansard roof providing habitable space on existing flat roof or on top of new story with skylights or dormers.
- Additional top story with flat roof to modern durability and thermal standards.
- Additional top story with new pitched roof, possibly containing skylights.

Vertical expansions are usually upward since there is almost available space upward that allows expansions. For example, roof space conversions are still a very common type of vertical expansion that provided the required extra space at a reasonable cost. Although downward expansions (i.e., basement adaptation) have been grabbing attention in the past few years, they are not still popular since they are significantly more expensive than upward expansions. In addition to the ncost factor, implementation of downward expansions is much more complicated than vertical expansions such as the need for soil condition testing.

A building's performance with regard to this sub-SPI is assessed based on considerations of the following measures at the design stage:

- There are means of access and exit regarding the site and the building during the vertical expansion activities to make less interruption to the surroundings people (e.g., noise, dust)

- Vertical expansions do not disturb the neighborhood access to light, view, and so forth.

- The flat-roof construction and detailing facilitate disassembles required for extensions or re-configurations of the space (e.g., prefabricated components, bolted connections).

- Substructure (foundation) has been adequately over-designed.

- Soil conditions can accommodate the extra loading associated with expansion (new basement or additional story).

Consequently, the PLF below can be used to calculate the performance level of the given building with respect to this sub-SPI:

$$PL_{AB1\text{-}2} = 25i + 12.5j \qquad i \text{ and } j = 0, 1, 2, 3, 4 \qquad [5.112]$$

Where i and j are the number of the above vertical expandability measures that have been highly and moderately considered at the design stage of the given building, respectively.

Eventually, when the PLs of the above sub-SPIs have been obtained, the PL of the AB1 SPI is calculated as:

$$PL_{AB1} = 0.6 \times PL_{AB1\text{-}1} + 0.4 \times PL_{AB1\text{-}2} \qquad [5.113]$$

5.4.3.2 Dismantlability (AB2)

This SPI considers damsmantlability of residential buildings. Dismantlability refers to the capability of a building's products, components, and assemblies, to be disassembled during the use phase (where applicable) and at the end of life phase in a safe, efficient, and speedy way (in part or in whole).

Due to continuous advancements in energy efficiency and governmental energy efficiency and enhanced building performance policies, building codes and standards are continually changing every few years. In addition, the occupants' expectations of buildings are increasing. These reasons increase the demand for new technologies in buildings. Deficiencies in buildings and their services occur because sometimes they are not capable to meet some of the user requirements and also new technological advancements. Moreover, wear and tear as well as deterioration of the building products and components require refurbishment in some parts of the building. Thus, the dismantlability capability of buildings is significant since it can provide easier and cost-effective possibilities to accommodate such technology upgrades and refurbishments also implementation of other adaptability strategies such as expandability.

Furthermore, when a building reaches its end of life, it is important that its parts can be easily taken apart and the corresponding materials, products, and components, are reusable or recyclable (i.e., reprocessable) as much as possible. This is mostly achievable in the case of buildings that are dismantlable. In addition to the resource reservation benefit and corresponding reduction in the environmental impacts resulted from the dismantability adaptation strategy, it also offers economic benefits of offsetting the end of life costs by implementation of waste management's reuse and recycling strategies.

In order for a building to perform well with regard to this SPI, it should be designed for disassembly by incorporating suitable design techniques at the design stage. The performance of a building with respect to the AB2 SPI can be evaluated by meeting the measures below:

- Use of mechanical connections such as bolt and nut fasteners should be preferred to less mechanical connections such as screws or nails and chemical connections such as adhesives and glues, where possible.
- Use of standard sized materials and products should be maximized to promote reuse.
- Use of recyclable materials and products should be maximized.
- Use of modular and prefabricated components and systems should be maximized, where possible.
- Use systems and components that are capable of accommodating potential increased performance requirements (e.g., anticipating future advanced HVAC systems).
- Strong interconnections between different layers including structure, services (heating, plumbing, etc.), and scenery (partitioning, ceiling, finishes) should be avoided.
- Number of different types of components should be minimized.

Depending on the degree of meeting the above measures (i.e., none, moderate, high), the performance level of the given building with regard to dismantlability is calculated as:

$$PL_{AB2} = 20k + 10l \qquad k \text{ and } l = 0, 1, 2, 3, 4, 5 \qquad [5.114]$$

Where *k* and *l* are the number of the above measures that have been highly and moderately incorporated in the design of the building, respectively.

5.4.3.3 Record keeping (AB3)

Availability of the explicit information on the building components and systems can assist with effective decision making with regard to adaptation options in future when the building experience its use and end of life phases. This can significantly prevent costly probing exercises to explore potential components and systems for changes.

The performance level of this SPI is assigned based on the availability of the following information categories:

a- Information regarding the degree of connections (i.e., levels of intervention) between the building layers such as site (geographic setting, urban location), main structure (foundation and load bearing elements), services (heating, plumbing, pipes, ducts, cables), scenery (fittings, partitioning, ceiling, finishes), and set (e.g. furniture).

b- Information regarding the adaptability options that have been designed for the building's future changes.

Accordingly, the PLF for this SPI was established as:

$$PL_{AB3} = 33.3n + 33.3m \qquad n = 0, 1, 2;\ m = 0, 1 \qquad [5.115]$$

Where n is 1 and 2 if at the end of design phase, the information category 'a' is moderately and fully available, respectively, and m is 1 if the information category 'b' is available.

5.4.3.4 Relative importance of the SPIs under AB

To develop a sustainability index for this SPC, in addition to the PLs of the three SPIs, their weights are also required. As stated above, adaptability and the associated indicators have not been well studied and established in the literature. Therefore, this research attempted to develop relevant indicators as a baseline to address the adaptability of residential buildings. Similarly, no studies were found that indicated the priorities of different features of adaptability by which their relative importance weights can be derived. Consequently, in this research, equal weights were assigned to the three SPIs under the AB SPC. Throughout this research, a number of experts that were met for different parts of the research were also communicated about this proposed weight set. Almost all consulted exerts confirmed equal weight set is a reasonable start point. However, the weight set can modified/revised based on future adaptability studies of single-family residential buildings.

5.4.4 Design and Construction Time (DCT)

The 'Design and construction time (DCT)' SPC considers the duration of residential building projects. This criterion is one of the indirect-impact economic SPCs and can significantly influence the project's economic performance.

As reported earlier in Chapter 4, this SPC was ranked first and second within the economic SPCs and the overall TBL SPCs, respectively. This showed the importance of the project schedule in construction experts' view. A significant difference between the modular and conventional construction methods is the fast turnaround between the breaking of ground and occupancy in the case of the former method. Unlike the conventional processes, construction of a building (manufacturing modules) and preparation of the final project site (foundations, etc.) can be performed simultaneously (Kawecki 2010; Haas et al. 2000), which can offer up to 40% savings in the construction time (Mah 2011; Lawson and Ogden 2010; Smith 2011; MBI 2012a). The resulted time saving can greatly contribute to project cost savings when using modular processes. In other words, speed of construction can enhance the economic performance since the developers/contractors can deliver the finished buildings to the end users (clients or potential buyers) faster and start new projects. On the other hand, the end users can occupy their buildings faster and eliminate unnecessary expenses such as rental. Furthermore, this can help the economy of the community the buildings are built.

Two SPIs have been determined under DCT including ‘DCT1 Design time’ and ‘DCT2 Construction time’. To establish a PLF for each of these SPIs, the information related to the least and most desirable performance values of design and construction time is required. However, because this information is dependent on the regulations and construction conditions within the region in which the building is constructed, it should be acquired locally. As described earlier in this chapter, in the cases of such locality sensitive SPCs, Survey B was designed and implemented based on the Delphi method to collect the required data from the construction firms in the Okanagan, BC. The details of Survey B and its implementation (design, participants, rounds of data collection) have already been described; therefore, are not repeated in this and next sections that discuss other locality sensitive SPCs. In addition to Survey B, the literature (such as local websites) was searched to support the findings from this survey.

It is also important to mention that the total design and construction time can be significantly different for building projects with different total floor area. Hence, the collected data was transformed to the time per functional unit of 1 ft^2 when establishing the PLFs for the SPIs under the DCT SPC. Similarly, the PLFs for the SPIs associated with ‘Design and construction costs (DCC)’, ‘Operational costs (OC)’, and ‘Maintenance costs (MC)’ were based on cost per 1 ft^2 of single-family buildings. Although the values of these SPCs do not change strictly linear with respect to building size, the experts suggested that the values follow approximately linear for single-family buildings with total floor areas under 3000 ft^2.

5.4.4.1 Design time (DCT1)

The design phase consists of the concept design stage, design development stage, and construction documents stage. In this research, the time required to obtain the required permits (i.e., permit stage) was also considered under this SPI. To determine the performance benchmarks for the design of conventional single-family buildings (up to 3000 ft^2 total floor area), the following questions were included in the questionnaire:

- What is the most desirable duration (i.e., the best time performance or the fastest duration) to receive legal permissions and design a single-family building without losing the design quality?
- What is the least desirable duration (i.e., the worst time performance or the longest duration)

to receive legal permissions and design a single-family building without losing the design quality?

It is worth to mention that, for any uncommon reason, the design time can be much longer that the least desirable time. For example, there is a possibility that a design firm does not have enough human resources at the time or had unpredictable number of design offers in a specific time of the year. In contrast, a design process for a building might be very fast in exceptional conditions. However, the survey's participants were asked to exclude such exceptions and consider regular conditions when assigning the least and most desirable time periods.

The least and most desirable performance values for the design time came to be 0.032 day/ft^2 and 0.016 day/ft^2, respectively. Consequently, the data variable (i.e., design time) range was determined and the PLF below was established by which the performance level of this SPI can be measured:

$$PL_{DCT1} = -6250DT + 200 \qquad 0.016 \leq DT \leq 0.032 \qquad [5.116]$$

Where DT is the design time per 1 ft^2 of the subject building (day/ft^2).

5.4.4.2 Construction time (DCT2)

The construction phase comprises all the activities to construct a building based on the design documents. As emphasized above, this phase is completely different between construction of a conventional building and a modular building. To identify the performance benchmarks for the construction duration of single-family buildings described before, the following questions were included in the questionnaire:

- What is the most desirable time (i.e., the best time performance or the fastest duration) to construct a single-family building without losing the construction quality?
- What is the least desirable time (i.e., the worst time performance or the longest duration) to construct a single-family building without losing the construction quality?

It is also possible that the construction duration becomes unreasonably short or long due to exceptional reasons (e.g., harsh weather). However, experts provided their opinions by considering regular construction circumstances in the Okanagan.

Consequently, the least and most desirable construction durations were obtained as 0.137 day/ft^2 and 0.101 day/ft^2, respectively. Accordingly, the following PLF was established for this SPI:

$$PL_{DCT2} = -2777.8CT + 380.56 \qquad 0.101 \leq CT \leq 0.137 \qquad [5.117]$$

Where CT is the time of constructing 1 ft^2 of the subject building (day/ft^2).

5.4.4.3 Relative importance of the SPIs under DCT

To develop a sustainability index for this SPC, the performance levels of the corresponding SPIs along with their weights are required. Although the data variable of both DCT1 and DCT2 SPIs are of the same unit (i.e., day/ft^2), their contributions to the parent DCT SPC are different; thus they have different importance weights. According to the results of Survey B, DCT1 and DCT2 account for 18% and 82% of a building project's total duration, respectively. Therefore, 0.18 and 0.82 were considered as the weights of DCT1 and DCT2, respectively, when developing the sustainability index for the DCC SPC.

5.4.5 Design and Construction Costs (DCC)

The DCC SPC investigates the economic performance of residential buildings in terms of the design and construction costs. This SPC is also one of the direct-impact economic SPCs. The design and construction of a building comprises the following cost items:

- Design including permits;
- Materials/products;
- Material/product/module transportations;
- Workforce;
- Equipment (machinery); and
- Office (off-site and on-site)

The costs associated with the design and construction phase of buildings are amongst major concerns of both construction practitioners (designers, engineers, contractors, developers) and users (occupants, clients) and can have a significant influence on the construction method selection. Supporting this, the DCC SPC ranked second and third under the economic SPCs and overall TBL SPCs, respectively (Chapter 4). Furthermore, this SPC ranked first among the direct-impact SPCs. This indicates that the costs associated with the design and construction phase of a building's life cycle grabbed more attention of the experts than the costs associated with other phases when comparing conventional and modular construction methods. Some literature and modular manufacturers discussed that using the latter method involves less costs compared to the former method (Haas et al. 2000; Lawson et al. 2012). For example, due to concurrent fabrication of several modules, less workforce and machinery transportation are needed. In addition, the required materials are purchased in bulk and therefore less expensive (Chiu 2012). However, this should be analytically investigated by adopting appropriate methodology and performing case study analyses of real projects. This was performed in this research by comparing the performance of modular building projects with the benchmark values of similar conventional building.

To facilitate quantification of the DCC SPC, two relevant SPIs were recognized: 'DCC1 Design cost and 'DCC2 Construction cost'. However, because the performance of this SPC is sensitive to the regional construction conditions (i.e., locality sensitive), the performance levels of its SPIs should be calculated based on local cost data (i.e., the Okanagan, BC). Therefore, to establish a PLF for each of these SPIs, the information regarding the least and most desirable performance values of design and construction costs was collected through conducting the same Survey B described earlier.

5.4.5.1 Design cost (DCC1)

The intent of this SPI is to calculate the performance of a given building with respect to its design cost. To determine the performance benchmarks for the design cost of conventional single-family buildings described before, the following questions were incorporated in the questionnaire:

- What is the best (cheapest) design cost (including conceptual planning, design, and permits) of a single-family building without losing the design quality?
- What is the worst (most expensive) design cost (including conceptual planning, design, and permits) of a single-family building without losing the design quality?

Finally, the least and most desirable design cost for 1 ft^2 of average-quality conventional single-family buildings in the Okanagan came to be 10.33 $\$/ft^2$ and 5.17 $\$/ft^2$, respectively. Subsequently, the data variable (i.e., design cost) range was finalized and the following PLF was established to calculate the PL of this SPI:

$$PL_{DCC1} = -19.38DC + 200.19 \qquad 5.17 \leq DC \leq 10.33 \qquad [5.118]$$

Where DC is the design cost of 1 ft^2 of the subject building ($\$/ft^2$).

5.4.5.2 Construction cost (DCC2)

The construction phase comprises all the activities to construct a building based on the design documents. As emphasized above, this phase is completely different between construction of a conventional building and a modular building. To identify the performance benchmarks for the construction cost of single-family buildings in the Okanagan, the participating experts in Survey B were asked the following questions:

- What is the best (cheapest) construction cost (including all the off-site and on-site work) of a single-family building without losing the construction quality?

- What is the worst (most expensive) construction cost (including all the off-site and on-site work) of a single-family building without losing the construction quality?

Consequently, the least and most desirable construction costs were obtained as 287.21 $/ft^2$ and 202.68 $/ft^2$, respectively. Accordingly, the data variable (i.e., construction cost) range was determined and the following PLF was established for this SPI:

$$PL_{DCC2} = -1.183CC + 339.77 \qquad 202.68 \leq CC \leq 287.21 \qquad [5.119]$$

Where *CC* is the construction cost of 1 ft^2 of the subject building ($/ft^2).

5.4.5.3 Relative importance of the SPIs under DCC

Although both DCC1 and DCC2 SPIs are monetary indicators whose data variables are of the same unit (i.e., $/ft^2), their contributions to the DCC SPC are different; thus they have different importance weights. Results of Survey B indicated that DCC1 and DCC2 account for 3% and 97% of the total design and construction costs, respectively. Consequently, the values of 0.03 and 0.97 have been considered as the weights of DCC1 and DCC2, respectively, when developing the sustainability index for the parent DCC SPC.

5.4.6 Operational Costs (OC)

Operational and maintenance costs are a part of buildings' life cycle costs. The quality of construction and the energy efficient equipment installed in a building during the design and construction phase has impacts on its operational performance during the use phase. This, consequently, can influence the economic performance of the building in terms of operational expenses. According to APEGBC/ACEC (2009), the long-term costs of operations and maintenance of infrastructure or building assets can be over 80% of the asset's lifetime costs. This shows the pivotal role of the engineering designs and the efficiency strategies incorporated in the design phase because it is during this phase that construction, operational, and maintenance cost savings can be most easily achieved.

In general, operational costs comprise two cost categories including 1) running costs such as energy bills; and 2) managing costs such as rental, insurances, local taxes and charges, and so forth (Krstić and Marenjak 2012; ISO 2008). In determining suitable SPIs under the OC SPC, at first glance, it appears that two SPIs each covering one of the above expense categories can be determined under the OC SPC. However, some expenses within the second cost category are mostly applicable for commercial, industrial, and multi-family buildings, not single-family buildings. Even those applicable expenses, such as rental and insurance, are regular expenses in every building and are not related to the design and construction of buildings; thus, the construction method (conventional and modular) has minimal impact on such expenses. Consequently, in this research, the first expense category has been considered as the only relevant SPI and named ‘OC1 Running costs’.

Because OC is also among the locality sensitive SPCs for which its SPI should be evaluated using local information, the required data for establishment of the PLF for this SPI was collected through the same Survey B. It should be pointed out that it is not an easy task to accurately calculate the ‘Operational costs’ and ‘Maintenance costs’ of a new building for its entire life span (e.g., 60 years) earlier in the design phase. These costs can only be estimated, otherwise it is required to observe and record these costs every year within the whole life span of the new building, which is not practical and applicable in this research or any similar research. Likewise, it is difficult to say what will be the ‘End of life costs’ after 50-60 years. Thus, in this research, the information regarding the annual OC and also MC of the existing buildings that have been constructed within the past few years with similar construction techniques (materials, services) were used to establish the PLFs for the SPIs under these SPCs. In other words, when implementing Survey B, the experts were asked to provide the estimated least and most desirable annual operational costs and maintenance costs of recently designed and built buildings in the Okanagan. Two reasons can be offered why the assumed buildings should be relatively new:

1) Buildings that have been built in the past few years have benefited from the same construction method and standards including type and quality of materials, heating and cooling technologies, among others, whereas old buildings have been constructed many years ago with different technologies and standards. Therefore, the provided estimates of OC and MC for the former buildings can be more similar (realistic) to new designs than the latter buildings.

2) As known, modular construction are relatively new method and not well-established compared to conventional construction. Therefore, the existing modular building have been constructed in the past few years and the OC and OM estimates provided by the modular builders for their case study modular buildings can be based on similar existing modular buildings.

5.4.6.1 Running costs (OC1)

This SPI evaluates the economic performance of the given building with respect to operational costs due to utility consumption. The data variable for this SPI has been defined as running costs (*RC*) which is the costs of utilities (energy and water). It is also important to note that energy and water consumptions are assessed and represented for the building as a whole rather than for individual systems or components of the building (Gardner 2013).

To estimate the least and most performance of single-family buildings in the Okanagan with respect to the OC1 SPI, the following questions were included in the survey:

- What is the best (cheapest) annual running costs including the utilities (energy, water) of a single-family building?
- What is the worst (most expensive) annual running costs including the utilities (energy, water) of a single-family building?

Consequently, the least and most desirable performance values for utility costs were obtained as 1.51 $\$/ft^2$/year and 0.80 $\$/ft^2$/year, respectively. Consequently, the PLF below was established to calculate the OC1 SPI:

$$PL_{OC1} = -140.85RC + 212.68 \qquad 0.80 \leq RC \leq 1.51 \qquad [5.120]$$

Where *RC* is the annual running costs per 1 ft^2 of the subject building ($\$/ft^2$/year).

5.4.7 Maintenance Costs (MC)

Maintenance costs comprise the costs of materials, systems, and labor and any associated services that are required to keep the building performance level in (or return it to) the state that it functions as it was intended and designed. Sufficient maintenance leads to prolong the service life of a building (Che-Ghani et al. 2016). As mentioned earlier, maintenance and operational costs account for significant portion of the total life cycle costs of buildings and awareness towards planning these costs is increasing (Krstić and Marenjak 2012).

Around 90% of the use phase of a building needs active maintenance, otherwise the full service of the building cannot be attained (Olanrewaju et al. 2011). One short-term solution to reduce a building' life cycle costs is to ignore maintenance expenses; however, in the long-term much more costs will be required for repairs and replacements (Che-Ghani et al. 2016). Several factors can influence a building's maintenance costs such as construction method, quality of materials, and performance of installed service equipment (Ali et al. 2010; El-Haram and Horner 2002; Al-Hammad et al. 1997). According to Krstić and Marenjak (2012), maintenance costs can be classified in the following groups:

- Statutory periodic inspections;

- Replacement or repairs of degraded materials and elements; and

- Reactive maintenance

All these groups are usually applicable to commercial and big residential buildings (e.g., high-rise, multi-family). However, according to experts, the second group is the most common and main contributor to maintenance costs in the case of typical single-family buildings including detached, semi-attached, and attached houses. Therefore, in this research, in determining suitable SPIs under the MC SPC, the ‘MC1 Repair and replacement costs’, was considered as the only relevant SPI. In addition, because MC is one of the locality sensitive SPCs, the required data for establishment of the PLF for this SPI was collected through implementation of Survey B.

5.4.7.1 Repair and replacement costs (MC1)

This SPI consists of the costs associated with repairing the buildings components and services such as repair of the heating system or replacing the degraded materials and components such as painting. It is ideal to have specific sub-SPIs that can represent different aspects of maintenance. However, this was not possible because the experts were only able to provide an estimate for annual maintenance costs of the whole buildings (not individual expenses). In addition, as described in the previous section, suitable assumptions were made in this research through which the experts were able to estimate the operational and maintenance costs based on the performance of recently buildings (the assumptions are not repeated again).

In order to acquire the local information for maintenance costs of single-family buildings in the Okanagan, the participating experts were asked the following questions:

- What is the best (cheapest) annual repair and replacement costs of a single-family building?
- What is the worst (most expensive) annual repair and replacement costs of a single-family building?

Finally, the least and most desirable performance values have been obtained as 1.45 $/ft^2$/year and 0.51 $/ft^2$/year, respectively. Therefore, the PLF below was established to calculate MC1:

$$PL_{MC1} = -106.38RCC + 154.26 \qquad 0.51 \leq RRC \leq 1.45 \qquad [5.121]$$

Where RRC is the data variable of the annual repair and replacement costs per 1 ft^2 of the subject building ($/ft^2/year).

5.4.8 End of Life Costs (EC)

Poor construction and use of buildings are important issues that increase the need for renovation of existing buildings and construction of new buildings. This results in consumption of huge energy and raw materials and generation of an enormous amount of C&D waste. In addition, because landfill disposal and incineration costs are low, much of the generated waste is sent directly to landfills and not recycled. Therefore, appropriate strategies for resource (material) efficiency in the design and construction phase and for waste management at the end of life phase of buildings should be implemented. As for resource efficiency in the design and construction phase, strategies such as waste prevention, use of recycled content, and reuse of components/materials from old projects in new projects, adaptability, and durability can effectively contribute to resource efficiency. These strategies have already been discussed earlier in present and previous chapters within the corresponding SPCs. Similarly, suitable waste management strategies can be implemented at the end of life phase of old buildings such that their components can be disassembles and reused in new projects and also the materials and products can be sent to recycling centers instead of landfills.

The EC SPC deals with the material efficiency at the end of life phase of buildings. However, even with considerations of effective strategies for material efficiency management in the design of a building, there is no guarantee to implement such strategies when the building reaches the end of its life. For example, even if a building has been designed for disassembly (e.g., prefabricated components), the reuse strategy is not implemented in majority of cases due to lack of an established and connected system by which the dismantled components can be reused in new projects. In addition, as stated above, due to the low costs of landfill disposal and incineration, there is less incentive for developers or contractors to implement the recycle strategy; therefore, much of the solid waste is not recycled.

Based on the above discussion, the end of life economic performance of a building is very difficult to be measured. This was confirmed when Survey B was conducted in this research to collect the data related to this SPC from the local firms (builders). According to the participating firms in Survey B, in almost all projects that a new building is to be built in a site where there is already an old building, they hire sub-contractors or waste management firms to perform the demolition tasks. The experts were only able to provide the demolition cost they pay. However, they did not have clear ideas on what happen to the materials and components of the demolished building in terms of implementing waste management strategies. Therefore, consensus was not made on the answers. Obtaining such detailed information is not easy and requires extensive data collection from sub-contractors or waste management firms who involve in construction and demolition projects, which is beyond the scope of this research. Even such data is available the same assumptions made for the OC and MC SPCs cannot be made for this SPC since this information cannot provide a reasonable estimate for end of life costs of new buildings. This is because old buildings were built over 50 (and more) years ago with different technologies, components, materials, and so forth, which are completely different than today's. Therefore, the end of life data of old buildings cannot be generalized and then conclude that the same end of life strategies will be implemented for new buildings after around 50 years at their end of life phases. In other words, due to significant differences in the construction technologies, old buildings that are now at the end of their life are not suitable representatives for new buildings in terms of end of life costs. Even if it is assumed that, the data of old buildings can represent the end of life costs of new buildings, no data of old modular buildings is available to be used for new modular buildings. This is because no modular building has reached the end of its life for which the implementation of waste management strategies and the associated costs could be observed and recorded.

Interestingly, this SPC was ranked the lowest among the economic SPCs by the construction practitioners (Chapter 4) which confirmed the above discussion from another perspective. This implied that, although modular buildings offer more potential waste management capabilities at their end of life, there is not a significant difference between the associated end of life costs of a conventional and a modular building in the current construction practices.

Based on the above discussion, measurement of the EC SPC and subsequently, the EC performance benchmarking of modular buildings have been relinquished in this research. It is worth to remind that, similar discussion was already made earlier in this chapter to justify why the 'Construction waste reuse' SPI cannot be a suitable SPI under the CWM SPC.

5.4.9 Investment and Related Risks (IRR)

This SPC evaluates investment on single-family building projects and the associated risks. Although this is mainly of the investors (e.g., developers, construction firms) interest to ensure the economic viability of a construction project before investment, the IRR SPC is considered as one of the important sustainability criteria. This is because investments in profitable projects can improve the whole economy of societies, especially when taking into account the high economic impacts of the building sector (e.g., worker employment, material market, building market).

A construction project is deemed economically feasible, if the expected profit meets or exceeds a pre-determined level of return on the investor's initial investment (Mohamed and McCowan 2001). The procedure of exploring this involves a degree of forecasting; therefore, decisions are frequently made based on past experience, either rationally or intuitively with some degree of uncertainty, and thus are made under risk (Moselhi and Deb 1993). In the case of big projects that involve long-term investments either in construction or later in operation (depending on the type of contract), such as infrastructure projects or high-rise commercial buildings, the total uncertainty is significant. Therefore, a detailed feasibility study is required before making any decisions on such investments.

However, in the case of small projects, such as single-family houses in which the construction and sale occur, in most of the cases, within a year, investments are short-term. Therefore, there is no need to predict and compare all the uncertainty related to the investment parameters such as interest rate, inflation, depreciation, tax rate, and operation life. Thus, the degree of uncertainty is not significant and could be minimal using past experience of similar projects in the region. Therefore, in this research, only one SPI that can adequately evaluate the investments on single-family building projects was determined under the IRR SPC as 'IRR1 Profitability of investment'.

5.4.9.1 Profitability of investment (IRR1)

This SPI investigates the profitability of a building project. Return on investment (ROI) is a common performance measure employed to evaluate the efficiency of a proposed investment by assessing its potential benefit (i.e., profit) (Misra and Mondal 2011; Giel and Issa 2011). To calculate ROI, the ratio of potential profits received as a result of an investment over the investment's cost(s) is taken and the result is expressed as a percentage or ratio (Giel and Issa 2011; Feibel 2003):

$$ROI = \frac{\text{Gain from investment} - \text{Cost of investment}}{\text{Cost of investment}} \qquad [5.122]$$

In the case of a building project, the above formula can be translated to the following:

$$ROI = \frac{SP - DCC}{DCC} \qquad [5.123]$$

Where SP is a building's sale price and DCC is the corresponding design and construction cost. It should be mentioned that, the DCC term in the above equation is the same DCC SPC that was discussed and the corresponding PLF was established earlier in this chapter.

Similarly, to establish a suitable PLF for SP, the associated least and most desirable sale performances were determined by including the following questions in Survey B:

- What is the least desirable sale price of single-family buildings, which delivers minimum or even negative profit?
- What is the most desirable sale price of single-family buildings, which delivers maximum profit?

Consequently, based on the survey findings, the least desirable sale (PL = 0) and the most desirable sale (PL = 100) are achieved when the constructed building is sold for S = 336.11 \$/ft^2 and S = 283.63 \$/ft^2, respectively. Therefore, the following PLF was established to calculate the performance level of the SP:

$$PL_{SP} = 1.906S - 540.45 \qquad 283.63 \leq S \leq 336.11 \qquad [5.124]$$

In an attempt to establish a straightforward and linear PLF for the IRR1 SPI, in the first step, the

ROI formula (Equation [5.123]) was simplified to 'profitability of investment (POI)' as:

$$POI = \text{SP - DCC} \qquad [5.125]$$

Which implies that a building project is profitable only when SP>DCC.

In the next step, the least and most desirable values for POI were determined using the boundary conditions of SP and DCC. That is, the most desirable POI is achieved when the sale price is the highest and the design and construction costs is the lowest. Contrary, the least desirable POI occurs when the sale price is the lowest and design and construction costs is the highest. However, as stated before, the indicators in this research are of two types: benefit indicators and cost indicators. For benefit indicators (e.g., SP), an increasing trend is desirable, while for cost indicators (e.g., DCC), a decreasing trend is desirable. In other words, the PL of 100 for a benefit indicator and a cost indicator is equivalent to their highest and lowest values, respectively. Therefore, when using the PL values of the SP and DCC indicators, Equation [5.125] should be revised as:

$$\text{Revised } POI = \text{SP + DCC} \qquad [5.126]$$

Eventually, by considering the above stated boundary conditions, the following PLF was established for the IRR1 SPI:

$$PL_{IRR1} = \frac{Revised\ POI}{2} = 0.5SP + 0.016DCC1 + 0.484DCC2 \qquad [5.127]$$

Where *SP*, *DCC*1, and *DCC*2 are the sale price, the design cost, and the construction cost per 1 ft^2 of a single-family building which are presented in their PL values. For example, the *PL* = 100 will be obtained for IRR when *SP*, *DCC*1, and *DCC*2 all are at the most desirable level (i.e., *PL* = 100) is 100. In contrast, the *PL* = 0 will be obtained for IRR when *SP*, *DCC*1, and *DCC*2, all are at their least desirable level (*PL* = 0).

5.5 Development of Sustainability Indices

In this section, the process of sustainability index development is discussed in details. As explained earlier in the methodology section, using a bottom-up approach, the proposed framework in this research develops aggregated sustainability indices at the following levels:

- Level 3: Sustainability indices for SPCs;
- Level 2: Sustainability indices for sustainability dimensions; and
- Level 1: Overall sustainability index.

The developed sustainability indices are used to benchmark the performance of the subject modular building. In this research, the aggregated sustainability indices for a given modular building are developed through systematic implementation of the TOPSIS MCDA method (see Appendix C for the detailed descriptions). The TOPSIS method, which is based on the relative closeness to the best performance and relative remoteness from the worst performance, provides a more realistic benchmarking approach.

5.5.1 Sustainability Indices for SPCs (Level 3)

For a subject building, first, the required data to calculate the PLs of all indicators (sub-SPIs and subsequently SPIs) related to a SPC is collected. The PL values are calculated using the performance level functions (PLFs) of the indicators established earlier in this chapter. Second, the sustainability performance index for each SPC is developed through the TOPSIS aggregation process by combining the calculated SPIs and their weights. This should be mentioned that in this chapter, at the end of each section that discussed a SPC and the corresponding SPIs, the weights of the SPIs were determined and presented.

The outcomes of the aggregation process are the sustainability indices for the environmental and economic SPCs (Level 3). Each index is denoted by adding the letter "*i*" to the end of the acronyms of the corresponding SPC such as *EPi*, *CWMi*, *DCTi*, and so forth. Similar to the performance levels of SPIs, the sustainability index for a SPC is presented in the form of a normalized value between 0 and 100, which represents the performance of the subject building with respect to the SPC.

It is necessary to remind that the sustainability index for the GE SPC has been developed using a separate methodology. As explained earlier in this chapter, the LCA method along with an AHP-based framework was used to develop a set of environmental impact indices. Since, the method of performance evaluation of modular building with respect to the GE SPC is different from the method used for all other SPCs, this SPC was excluded from the process of development the sustainability indices at Level 2 and then Level 1 below.

5.5.2 Sustainability Indices for Sustainability Dimensions (Level 2)

After developing the sustainability indices for the environmental and economic SPCs, the assessor might be interested in evaluating the performance of the subject building with regard to any of the sustainability dimensions. In this research, the sustainability index for a sustainability dimension (Level 2) is developed using the same aggregation process (TOPSIS method). Subsequently, the developed sustainability indices of the SPCs associated with the intended sustainability dimension and the relative importance weights of the SPCs are aggregated.

To determine the weights of the SPCs within each sustainability category, the results of the ranking analyses conducted in Chapter 4 were used. As reported in that chapter, Survey A was designed and conducted to capture the construction industry's feedback on applicability of the compiled SPC categories for sustainability assessment of residential modular buildings. Then, using the ranking analysis, the severity index (SI) of each SPC was calculated. Subsequently, the SPCs were ranked within their sustainability category based on their SI values and an importance level was assigned to each SPC according to the following severity scale (Tables 4.4-4.6):

- Extremely High (EH): $SI \geq 95.00\ \%$
- Very High (VH): $85.00\ \% \leq SI < 95.00\ \%$
- High (H): $75.00\ \% \leq SI < 85.00\ \%$
- Medium (M): $65.00\ \% \leq SI < 75.00\ \%$
- Low (L): $55.00\ \% \leq SI < 65.00\ \%$
- Very Low (VL): $45.00\ \% \leq SI < 55.00\ \%$
- Extremely Low (EL): $SI < 45.00\ \%$

The SI values of the SPCs were used to determine the weights of SPCs within the environmental and economic SPC categories. In the above severity scale, the minimum SI value for a SPC (i.e., the lower bound) by which an importance level of 'Low' can be assigned had been defined as $SI = 45\%$. In other words, it can be assumed that if the SI value for a SPC came to be less than 45%, the SPC has no importance (i.e., 'Extremely Low') in the sustainability assessment process of modular buildings. Considering this, the weights of the SPCs were calculated. It is important to note that, since the 'Material consumption in construction (MCC)' and 'End of life costs (EC)' were eliminated from the selected SPCs, the weights of the environmental and economic SPCs have been readjusted. Similarly, if for any reason, such as the study scope, data collection limitations, assessor/decision maker's preference, and so forth, a limited number of SPCs are selected for assessment, the weights of the selected SPCs should be readjusted by excluding the eliminated SPCs. The normalized weights of the environmental and economic SPCs were listed in Table 5.14.

Table 5.14 Relative importance weights of the selected environmental and economic SPCs

Environmental category	Weight	Economic category	Weight
Construction waste management (CWM)	0.214	Design and construction time (DCT)	0.157
Energy performance and efficiency strategies (EP)	0.210	Design and construction costs (DCC)	0.152
Site disruption and appropriate strategies (SD)	0.168	Durability of building (DB)	0.123
Renewable and environmentally preferable products (REP)	0.150	Integrated management (IM)	0.120
		Investment and related risks (IRR)	0.117
Regional (local) materials (RM)	0.130	Operational costs (OC)	0.114
Renewable energy use (RE)	0.128	Adaptability of building (AB)	0.109
		Maintenance costs (MC)	0.108

In addition, because the social sustainability assessment of modular buildings is outside the scope of this research, the weights of the social SPCs were not included in this table.

Aggregation of the calculated SPCs (i.e., sustainability indices of SPCs) and their weight develops the sustainability indices for the environmental and economic dimensions, which are denoted by *ENVRi* and *ECONi*, respectively. Each of these indices, similar to the indices at Level 3, is represented between 0 and 100 and provides a picture of the subject modular building's performance with regard to the corresponding sustainability dimension.

5.5.3 Overall Sustainability Index (Level 1)

The inputs of the last aggregation process are the sustainability indices for environmental and economic dimensions of sustainability (*ENVRi* and *ECONi*) along with the relative importance weights of these dimensions and the output is the overall sustainability index named *OVERALLi*. This index represents the life cycle sustainability performance of the subject modular building.

To determine the required weights of the sustainability dimensions, within the same survey explained in Chapter 4 (Survey A), the construction practitioners had been asked to assign weights to the TBL sustainability dimensions. Subsequently, the weights of the environmental, economic, and social dimensions came to be 0.361, 0.406, and 0.233, respectively. The weight of economic dimension came to be higher than the weights of both environmental and social dimensions perhaps because the economic aspect of construction projects is always one of the main concerns of construction practitioners. Remarkably, this result is consistent with the results of the survey for SPC ranking where the economic SPCs were rated higher than other environmental and social SPCs by the construction experts.

Since in this research only the environmental and economic performances of modular buildings have been investigated, the weights of these two dimensions were readjusted and normalized to use in the above aggregation process. Consequently, the weights of the environmental and economic dimensions were determined as 0.471 and 0.529, respectively.

5.6 Summary

This chapter discussed the development of sustainability indices for performance benchmarking of residential modular buildings. First, suitable measurable indicators (i.e., SPIs and sub-SPIs) associated with each selected environmental and economic SPC were determined. For all indicators, their measurement methods, their weights, their least and most desirable performance values (benchmarks), and corresponding ranges of data variables were determined using the literature and experts' opinions (surveys and interviews). Subsequently, a performance level function (PLF) was established for each indicator by which its performance can be calculated, normalized, and represented based on a performance level (PL) between 0 and 100.

To evaluate the performance of a given modular building, suitable sustainability indices should be developed. To this end, the required data specified under each sub-SPI and SPI should be collected from the subject modular building project. Then, using the established PLFs, the PLs of the indicators are calculated. Eventually, the calculated PLs of the indicators associated with each SPC and their weights are combined through the TOPSIS MCDA aggregation process to develop the sustainability indices for the SPCs (Level 3). Using a bottom-up approach, the sustainability indices can be developed at upper levels for each sustainability dimension (Level 2) and for the overall sustainability (Level 1) by performing similar aggregation process. The developed sustainability indices are then compared to the performance benchmarks of the corresponding conventional residential buildings. These performance benchmarks can be established and presented in the forms of sustainability performance scales at each level to facilitate such comparisons (Chapter 6).

Development of the sustainability indices using the methods established in this chapter depends on the scope of study and also on the availability of the required data related to the subject building. Therefore, depending on circumstances of the subject building, the decision maker (DS) or assessor might choose a limited number of SPCs for quantification and assessment.

Chapter 6 Integrated Framework for Sustainability Assessment of Modular Buildings

Parts of this chapter will be submitted for possible publication in:

- *Sustainable Cities and Society* entitled "Environmental sustainability benchmarking of modular homes – Part II: Performance assessment" (Kamali et al. 2019b).

- *Journal of Cleaner Production* entitled "Economic sustainability benchmarking of modular homes – Part II: Performance assessment" (Kamali et al. 2019d).

In this chapter, the sustainability performance scales (SPSs) are established. In addition, as the main output of this thesis, a multi-level decision support framework is developed that can be used to comprehensively assess the sustainability performance of residential modular buildings.

6.1 Background

The primary goal of this research is to improve sustainable construction by developing a methodical and practically applicable life cycle sustainability performance assessment framework for residential modular buildings. The adopted performance assessment methodology is to compare (i.e., benchmark) the environmental and economic performances of modular buildings with the corresponding performances of their conventional counterpart. Different definitions have been provided for benchmarking. In general, benchmarking is applied to a wide variety of activities, products, services, and practices, to compare the current performance level with others and/or learn from them to identify, adapt, and adopt practices to improve the performance as illustrated in Figure 6.1 (Camp 1989; Stapenhurst 2009).

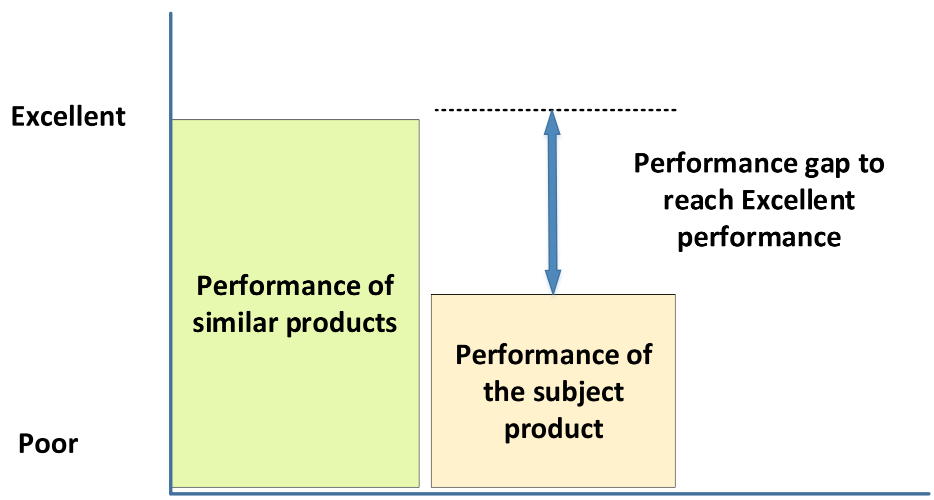

Figure 6.1 Performance benchmarking to identify the performance gap of a product

In recent years, benchmarking studies have been directed to evaluate the performance of a product or service by comparing it with the performance of its counterpart(s) or with its own historical performance, as appropriate, using a set of key performance criteria/indicators (also named KPC, KPI, PC, PI) (Thomas and Thomas 2008). Performance criteria/indicators as early warning signs provide useful information to reduce uncertainty and to take appropriate actions to improve the performance of a product, process, or service (Kerzner 2017; Lu et al. 2015).

Similar to other industries, in the construction industry, researchers have showed increasing interest in adaptation of benchmarking methods based on evaluation of a set of performance criteria (Cheung 2010; Horta et al. 2009). Lin et al. (2011) evaluated the success of construction projects by performance benchmarking using a set of indicators. Hegazy and Hegazy (2012) developed a benchmarking model based on financial performance indicators to assess the business performance of construction firms. In another study, Horta et al. (2009) integrated KPIs and data development analysis to benchmark the performance the construction industry. Benchmarking studies with performance indicators have also performed to examine the success of construction waste management (Ball and Taleb 2011).

In this research, a benchmarking method based on analyzing performance criteria/indicators was chosen to assess the life cycle sustainability of residential modular buildings. In this regard, first, suitable sustainability performance criteria (SPCs) for residential modular buildings were identified, prioritized, and selected (Chapter 4). Subsequently, an attempt was made to determine suitable measurable sustainability performance indicators (SPIs and sub-SPIs) under each selected SPC. Afterwards, the aggregated sustainability indices were developed that represented the performance of the subject building at different levels, i.e., SPC (Level 1), sustainability dimension (Level 2), and the overall sustainability (Level 3) (Chapter 5). In order to evaluate the performance of a modular building, the developed sustainability indices should be compared with the performance benchmarks of similar conventional buildings. To this end, the first part of this chapter established a set of sustainability performance scales (SPSs) to represent the performance benchmarks of conventional buildings at the aforementioned levels. Establishment of these SPSs was the last requirement for life cycle sustainability performance assessment of residential modular buildings in this research. Thus, the second part of this chapter incorporated all research outcomes (i.e., methodologies, frameworks, and deliverables) into an integrated sustainability assessment framework as a multi-level decision support framework (DSF).

6.2 Detailed Methodology

Figure 6.2 illustrates the methodology steps used in this chapter that leads to establishment of sustainability performance scales (SPSs) and development of the decision support Framework (DSF) for residential modular buildings. These steps have been explained in detail in this section.

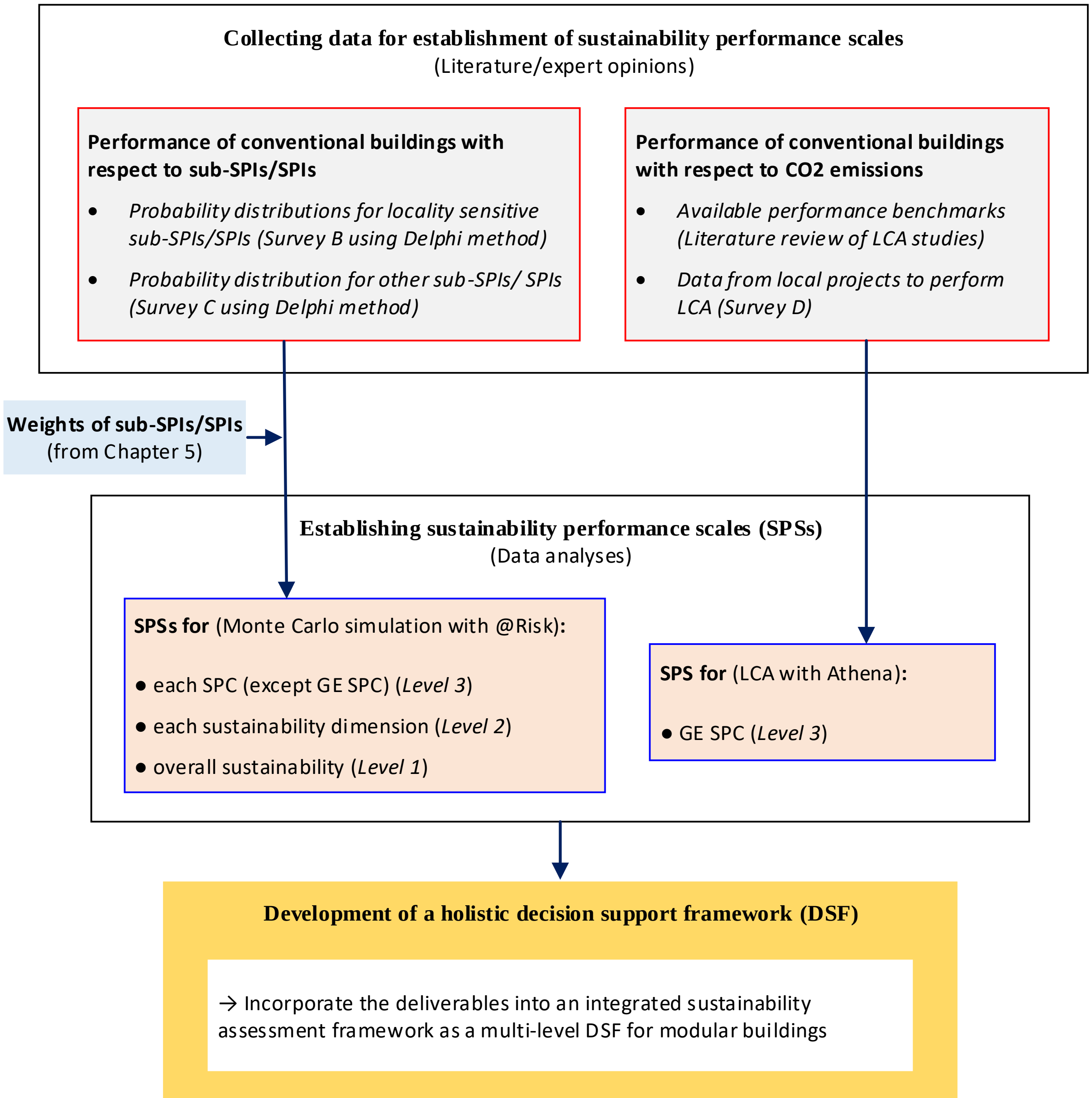

Figure 6.2 Methodology used in Chapter 6

6.2.1 Data Collection

As discussed before, the SPCs are assessment areas that can comprise a number of measurable indicators, i.e., SPIs, and sub-SPIs. Typically, a SPC cannot be directly calculated unless the associated measurable indicators are determined. Similarly, it is not usually expected to explicitly find the performance benchmarks of a SPC in the literature. However, by ascertaining the performance benchmarks of the associated SPIs and sub-SPIs and then combining these performances using suitable methods, the performance benchmarks of the SPC can be established. To collect the required data, the following potential data sources can be used:

- A database that contains the historical performance of single-family conventional buildings with respect to each SPI and sub-SPI.
- Opinions of experienced experts on the historical performance of single-family conventional buildings with respect to each SPI and sub-SPI.

Because the first data source was not available in the literature for many of the indicators, an attempt was made to collect the required data using the second data source. In this regard, two questionnaire surveys, i.e., Survey B and Survey C, were designed by which experts' feedback on the historical performance of buildings with respect to the sub-SPIs and SPIs (developed in the previous chapter) has been captured. Both surveys were designed and conducted according to the Delphi method. The Delphi method has been described in the previous chapter and is not repeated in this section.

Usually, experts can provide certain information when they are asked specific questions rather than broad questions. For example, an expert might have an idea on the historical performance of buildings with regard to the amount of 'generated waste'. However, he/she might not have an assured opinion on the performance of buildings with respect to a broader indicator such as 'waste management strategies' that itself consists of a number of indicators including the 'generated waste'. The concept of 'independency' can shed a light on this. Independent indicators are defined in this research as those that there are not any indicators attached to them; therefor, their values can be measured independently using their PLFs by having the data of their data variables. In this regard, all the sub-SPIs in this research are independent indicators and the associated SPIs are dependent. However, in some cases, there are not any sub-SPIs attached to a SPI; thus, such SPIs are also independent indicators that can be directly measured using their PLFs by having the data of their data variables. In other words, the independent indicators ask the most specific questions on the associated data variable. Therefore, the approach in the design of both Survey B and Survey C was to include all the independent indicators in these questionnaires. Subsequently, by using the collected data through these surveys, the performances of conventional buildings with respect to all independent indicators were determined. Then, the performances of conventional buildings with respect to the dependent SPIs were determined by combining the performances of the corresponding sub-SPIs using a suitable simulation method. The same process continued to determine the performances of conventional buildings with respect to the SPCs (Level 3), sustainability dimensions (Level 2), and overall sustainability (Level 1).

In this research, the only SPC among all the selected environmental and economic SPCs for which the experts were not able to explicitly provide the information regarding the performance benchmarks of its SPIs was ‘Greenhouse gas emissions (GE)’. This was anticipated since such information is obtained based on the results of LCA studies, which are not usually performed and reported for single-family buildings. Therefore, it was not possible to establish a sustainability performance scale (SPS) for the GE SPC. As mentioned in the previous chapter, a different methodology based on LCA analyses was used to benchmark the GE performance of modular buildings. Therefore, a separate survey (Survey D) was designed and implemented to collect the data required for the LCA analyses.

6.2.1.1 Design and implementation of Survey B

The main difference between Surveys B and C is the type of SPCs and the associated SPIs and sub-SPIs incorporated in each survey. As discussed before, some of the economic SPCs, such as ‘Design and construction costs (DCC)’, are high locality sensitive and the information regarding their performance should be collected locally based on the construction conditions and circumstances of the region the buildings are constructed. Therefore, the questions regarding this type of SPCs were included in Survey B. It is important to remind that this survey is the same Survey B conducted in the Chapter 5. As mentioned before, Survey B was initially designed to determine the least and most desirable performances of conventional buildings with respect to the SPIs correspond to the locality sensitive SPCs to establish the associated performance level functions (PLFs). To establish the sustainability performance scales for these SPCs, the questions regarding the historical performance of single-family conventional buildings with respect to the independent indicators under these SPCs were also included in the same survey. Since the same participating experts also provided their feedback to these additional questions during the same rounds of the Delphi method, the descriptions of this survey are not repeated again (see Section 5.4 for details).

6.2.1.2 Design and implementation of Survey C

As discussed before, in cases where the data on the performance of buildings is available for the world, country, province, and city, the priority is to use the local data (e.g., city) for establishment of the performance benchmarks. This is because more local data provides more realistic picture of the historical performance of buildings in the region. However, according to the rating systems, the performance of buildings that are constructed in areas with similar construction conditions and climate zone, are almost the same for the most of the environmental criteria. This might be the reason why these systems established their scoring systems for broader areas such as the whole country mostly based on the climate zones than provinces and cities. Consequently, it is not necessarily required to collect the data for establishment of benchmarks of such environmental and economic criteria from the local experts and every experienced expert who is familiar with the performance of buildings in the areas with similar construction conditions and the same climate zone can assist.

In this research, Survey C was designed to collect the information regarding the performance of single-family conventional buildings with respect to the all independent sub-SPIs and SPIs associated with the selected environmental SPCs and those economic SPCs that are not high locality sensitive (i.e., IM, DB, AB). Since the case study modular buildings in this research have been designed and constructed in the Okanagan, this survey asked about the performance of the conventional buildings constructed in the Okanagan and other areas in BC with similar construction conditions and the same climate zone.

In the first section of Survey C, general descriptions of the survey (e.g., objective, benefits, duration, completion instructions, confidentiality, and contact information) along with the consent form were included. Then, in the second section, the main questions regarding the performance of conventional buildings with respect to the independent sub-SPIs and SPI under the above stated SPCs were included. The total number of these independent indicators came to be 81, which caused Survey C to be a lengthy survey. However, it had been designed in a way that the format and type of questions were straightforward and easy to follow. The data variables and their applicable ranges of the SPIs and sub-SPIs have already been developed in the previous chapter. Subsequently, the experts were asked to provide their feedback on the most likely value (i.e., expected value) of each data variable within its applicable range based on the performance of conventional buildings. It should be added that in cases where the performance benchmarks of buildings with respect to a SPI or a sub-SPIs could be different in different parts of the BC province (despite the same climate zones), an attempt was made to collect information specific to the Okanagan.

In search for the data and also suitable experts to participate in this survey, Canada Green Building Council (CaGBC) and BC Housing were initially contacted by emails. Since 2002, CaGBC has been promoting environmentally sustainable buildings and community development. BC Housing organization is a provincial crown corporation under the Ministry of Municipal Affairs and Housing that, since 1967, has been developing, managing, and administering a wide range of housing options across the province of BC. CaGBC did not provide any information regarding the sustainability performances of the building projects mentioning that the information of different building projects is private and subject to confidentiality. However, BC Housing cooperated in the research. Following call sessions and in-person meetings with officials at BC Housing's central office in Vancouver, BC, a number of experts were introduced and their contact information was received. The experts were then contacted, the research were explained, and their participation were requested. Three experts showed interest in the research. They were all knowledgeable professionals who have been involved in many building projects in BC. Furthermore, they were experienced in the field of green and sustainable buildings and also rating systems such as LEED. To consolidate the results of the survey, one construction firm (comprised an expert team) and one individual expert who have been involved in many building projects in the Okanagan were requested to participate. In addition, the search found a report published by BC Housing that discussed the most likely performance values of buildings with respect to a number of indicators determined in this research (BC Housing 2018). However, according to BC Housing officials and the participating experts, the report was not accurate such that BC Housing officials even mentioned that they decided to remove it from their website. Thus, the focus was mainly on the information provided by the participating experts.

Similar method used in Survey B was also used in Survey C to collect the required data. Therefore, the details of the Delphi method is not repeated again (see Section 5.4 for details). Eventually, within three rounds of data collection, the consensus was reached on the most likely performance values and the probabilities of possible outcomes of the independent indicators.

6.2.1.3 Design and implementation of Survey D

The performance of modular and conventional buildings with respect to the GE SPC can be evaluated by conducting LCA studies and comparing the calculated environmental impact measures (e.g., GWP) due to each construction method. Such LCA studies for single-family buildings in the Okanagan or even in BC were not available in the literature and have not been conducted and reported by any local or provincial organization/construction firm. Only one LCA benchmarking study has been conducted in BC, which was for benchmarking multi-family buildings (Bowick and O'Connor 2017). Therefore, as stated before in Chapter 5, to gain a realistic understanding of the GE performance of single-family buildings, the LCA analyses were conducted for three case study buildings (including one conventional and two modular) in the Okanagan. To collect the required data for LCA analyses from the local homebuilders of these three benchmarking buildings, a separate survey, i.e., Survey D, was designed and conducted The details of the required data and the LCA software used in this study (Athena) have already been explained in the past section (Sections 5.3.7.1 to 5.3.7.4).

Similar to all other surveys designed in this research, general descriptions of the survey (e.g., objective, benefits, duration, completion instructions, confidentiality, and contact information) and the consent statement were included in the first section of Survey D. Then, in the second section, the general information of the building project for which the data is provided (size, number of stories, location, life span, and so forth) was asked followed by the questions about the project's data required for the LCA study.

6.2.2 Monte Carlo Simulation Analyses

The collected data via the surveys provided the past performance benchmarks of conventional buildings with respect to each of the independent sub-SPIs and SPIs. In the next step, the performance benchmarks of the sub-SPIs should be combined to develop the performance benchmarks of the corresponding SPIs. Similarly, the performance benchmarks of the SPIs should be combined to develop the performance benchmarks of the associated SPCs. However, simple aggregation of these performance benchmarks involves many uncertainties, thus can be misleading. To overcome these uncertainties, using a bottom-up approach, the performance of buildings with respect to each SPI can be generated by randomly and repeatedly aggregating the performance of related sub-SPIs. Similarly, the performance benchmarks of each SPC can be simulated using the generated benchmarks of the related SPIs. This process can continue up to generating the overall sustainability performance benchmarks of buildings.

There are various methods of simulation. One of the effective and highly used methods is the Monte Carlo simulation (MCS) method. Developed in the 1940's, MCS is a method of analysis that employs statistical sampling techniques to generate probabilistic approximations of the solution of a mathematical model or equation (EPA 1997). The core idea of the MCS method is to use random samples of parameters (i.e., random variables) or inputs to explore the behavior of a system or process. One of the most important parts of every MCS analysis is to construct appropriate probability distributions of the contributing parameters (i.e., random variables) of the system to ensure the validity of the outputs.

To this end, in this research, the collected data via the survey was used to construct suitable probability distributions of the independent indicators. Then, the generated probability distributions of all sub-SPIs under a SPI have been combined using the MCS technique to generate the probability distribution of the SPI. Similarly, the probability distributions of all SPIs related to a SPC were aggregated to generate the probability distribution of the SPC. It is important to note that the probability distributions of the SPIs under a SPC can be a combination of the probability distributions generated as the output of the previous MCS analyses (i.e., dependent SPIs) and the probability distributions constructed directly based on the results of the surveys (i.e., independent SPIs). In the same way, the generated distributions of SPCs were used as the input of new analyses to generate the distributions at a higher level, i.e., probability distributions of the environmental and economic performances of conventional buildings. Eventually, these two probability distributions were combined to simulate the overall sustainability performance of conventional buildings in the past years.

6.2.2.1 Probability distribution of a random variable

The number of possible outcomes of a random variable may be finite, countable infinite, and infinite. A discrete random variable X is a variable whose possible outcomes are obtained by counting and can be listed as a sequence (i.e., xi = x1, x2,…). Possible outcomes of a discrete random variable should be either finite such as the number of heads when flipping three coins, or countable infinite such as the set of all nonnegative integers. Whereas, a continuous variable is a variable whose possible outcomes are obtained by measuring such as the height of students in a class. Possible outcomes of a continuous random variable are infinite and can be any real value in an interval of values (Starnes et al. 2010).

The probabilities of occurrence of possible outcomes of a random variable can be formulated by a probability function. In the cases of continuous random variables, such function is called probability density function (PDF) that represent the probability that the random variable falls within an interval. In the cases of discrete random variables, such function is called probability mass function (PMF) rather than probability density function since it expresses the probability of occurrence of each possible outcome of the random variable (EPA 1997). In other words, while a PMF assigns probabilities to precise values of possible outcomes, a PDF assigns probabilities to intervals that are lying between any two precise values of outcomes (Stewart 2011).

The PMFs and PDFs can be visualized in graphical form called probability distribution (also called probability histogram) by which the possible outcomes of a random variable and corresponding probabilities (likelihoods) are illustrated. As shown in Figure 6.3, the horizontal axis of the probability distribution for a PMF represents the possible outcomes of the discrete variable X (i.e., X= 0, 1, 2, 3, 4, 5, 6, 7, 8, 9), and the vertical axis represents the corresponding probabilities, P(X). All probabilities assigned by a PMF must be nonnegative and between zero and one. They must also add up to the total probability of 1.

On the contrary, a continuous random variable X may take any value (i.e., any real number) within a defined range. Therefore, the probability of X having any precise value within that range is extremely small because a total probability of 1 must be distributed between an infinite number of values. That is, the probability that a continuous random variable X is exactly equal to a certain value of outcome is zero. As illustrated in Figure 6.3, the vertical axis of the probability distribution of the continuous variable X (i.e., f(X)), does not represent probabilities; whereas, the integral of f(X) represents the probability that a random variable falls within an interval, i.e., $P(X) = \int f(X)$. In other words, the probability of an interval lying between two precise values of X is obtained by calculating the area under the part of the curve associated with the interval. Therefore, the total area under the curve must be 1 since it states the probability of occurrence of all possible outcomes (Starnes et al. 2010).

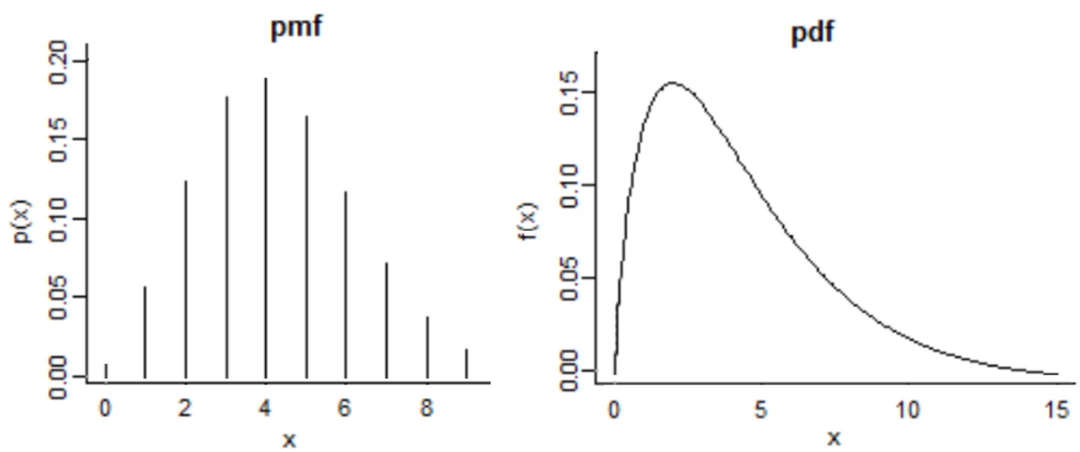

Figure 6.3 Probability distributions of discrete random variables (PMF) and continuous random variables (PDF)

6.2.2.2 Selection of probability distribution type

As stated earlier, one of the most significant parts of every MCS analysis is to construct appropriate probability distributions of the contributing data variables as the input of the analysis. Various types of common probability distributions for both discrete and continuous random variables are available with different characteristics, advantages, and weaknesses. However, selection of the most suitable distribution depends on the type and availability of data for the data variables in a study.

The random variables in this study are the independent indicators (sub-SPIs and SPIs). For each indicator, a suitable probability distribution types should be selected that is capable to effectively present the historical performance of buildings based on the collected data (i.e., experts' opinions). As discussed before, the PLF of an indicator calculates and presents its performance level (i.e., possible outcome) in a value between $PL = 0$ and $PL = 100$. However, an indicator is either a discrete or a continuous random variable. That is, the possible outcomes of a discrete indicator are limited number of PL values. On the contrary, possible outcomes of a continuous indicator are infinite and can be any PL between 1 and 100. For example, depending on meeting the lighting measures in a building, the possible outcomes of the corresponding PLF of the 'Efficient lighting' indicator are 0, 17, 33, 50, and 100. Whereas, building projects produce different quantities of waste generated ratio (WGR) within the WGR's applicable range; thus, the corresponding PLF of the 'Construction waste diversion' indicator, can result any PL between 0 and 100.

In general, in order to convince a potential participant to participate in a research survey (i.e., questionnaire, interview), aside from its topic and benefits, the number of questions included in the survey should be kept as minimum as possible. The questions should also be uncomplicated and easy to understand. In the case of Surveys B and C, several sub-SPIs and SPIs were incorporated and their performance benchmarks were intended to be determined based on the experts' opinions. However, as exemplified above, the possible outcomes of each indicator can be a limited number of PL values to infinite PL values. Therefore, it is not reasonable to expect the experts to assign probabilities of occurrence to uncountable number of possible PLs. Even if impracticality of the survey implementations due to the numerous number of questions is overlooked, the results of continuous indicators can be misleading and unrealistic since no expert can precisely assign a probability to each (interval) of the infinite possible outcomes of a continuous random variable.

In the cases of the discrete indicators, since the number of possible outcomes for each indicator was reasonably low, an attempt was made to determine the probability of each possible outcome based on the expert opinions provided in Surveys B and C. However, in the cases of the continuous indicators, the literature was searched to find suitable distribution type by considering the above stated limitations. Consequently, the triangular distribution was found as a suitable probability distribution to present the collected data. In recent years, the triangular distribution has been gaining attention because of its application in MCS method (Wright 2002; Banks et al. 2010). In cases where there is limited sample data available, in particular, when the relationship between variables is known but limited data is available; this distribution is often chosen (Garg et al. 2009). It is also known as lack of knowledge distribution, which can be constructed by minimal data. The math of the triangular distribution is relatively simple and it nearly approximates a lognormal distribution that can effectively model the skewed distributions (Lampe and Platten 2015).

According to Mun (2008), the triangular distribution describes a situation where the minimum (also called Min, lower limit, lower bound), maximum (also called Max, upper limit, upper bound), and most likely (also called Mode, likely, expected) outcomes of a random variable are known. The Mode falls between the Min and Max values, forming a triangular-shaped distribution, which shows that values near the minimum and maximum are less likely to occur compared to values near the most likely value.

In this research, the Min and Max parameters in the triangular distribution are PL = 0 and PL = 100 correspond to the least and most desirable performance values of each SPI (and sub-SPI), respectively. These lower and upper bounds have been determined in the past chapter when establishing the PLFs of each indicator. Therefore, the only data required for construction of the probability distribution of a continuous indicator was its most likely PL value that has been obtained based on the experts' feedback in Surveys B and C.

6.2.3 Establishment of Sustainability Performance Scales

As discussed before, to benchmark the performance of the subject modular building, the sustainability indices that were developed at different levels should be compared with the performance of similar conventional buildings at the corresponding levels. Therefore, to facilitate such comparisons, a set of sustainability performance scales (SPSs) correspond to different levels (Levels 3, 2, and 1) are required.

After the probability distributions of the independent sub-SPIs and SPIs were constructed, the MCS analyses through multiple rounds were conducted to generate the probability distributions of the corresponding parent indicators and criteria. To this end, the @Risk software as a powerful tool for MCS analysis was used. This software is an add-in to Microsoft Excel that lets the user to perform MCS and provides virtually all possible outcomes for a system or process and how likely they are to occur. As explained earlier, the outputs of the MCS analyses at each level were a set of probability distributions that represent the historical performance of conventional buildings at that level. For example, the results of the MCS analyses at SPC level (i.e., Level 3) were a set of probability distributions, each of which represented the (simulated) performance of buildings with respect to a SPC.

To establish appropriate SPSs, a suitable evaluation scale should be used to divide the total range of possible PL outcomes of each distribution ($0 \leq PL \leq 100$) into a number of common performance categories, such as Poor to Excellent or Low to Outstanding. In this regard, the literature with the focus on the sustainability rating systems was searched to check the existing evaluation scales for performance evaluation of buildings. Each sustainability performance system has its own method of scoring and evaluation scales. For example, the LEED rating system assigns points when each of its criteria is met by an average-sized building project. The building is then evaluated (certified) by comparing the total earned points (out of 136 available points) with five certification levels including Uncertified (0-44), Certified (45-59), Silver (60-74), Gold (75-89), and Platinum (90-136) (CaGBC 2009; USGBC 2018). As another example, the BREEAM rating system uses an evaluation scale that comprises Unclassified (scores <30% of maximum score), Pass (30% ≤ score < 45%), Good (45% ≤ score < 55%), Very Good (55% ≤ score < 70%), Excellent (70% ≤ score < 85%), and Outstanding (85% ≤ score) (BRE 2016). Likewise, Green Globes assigns globes from one globe representing the acceptable performance to five globes representing the best performance of the subject building (GBI 2015).

To gain a better understanding, these different evaluation scales were normalized to a range between 0% and 100%. Remarkably, regardless of different evaluation scales used and the corresponding performance categories, the thresholds of the performance categories were highly consistent between the reviewed documents. For example, any score under 30%, 25%, and 33%, is considered as unclassified (BREEAM), no globe (Green Globes), and uncertified (LEED), respectively. In the next interval, a score up to 45%, 40%, and 44%, has been evaluated as Pass (BREEAM), one globe (Green Globes), and certified (LEED), respectively. This means that, regardless of using different scoring systems and evaluation scales, all of the rating systems follow similar pattern when setting the thresholds for their performance categories.

Considering all these factors, this research proposed an evaluation scale that comprised four performance categories including Low, Fair, Good, and Excellent as shown in Figure 6.4. To establish a SPS, the possible range of PL outcomes (i.e., $0 \leq PL \leq 100$) should accommodate the four performance categories. To this end, three PL values within $0 \leq PL \leq 100$ that can act as the PL thresholds between every two performance categories should be determined. First, the percentage values (scores) used in the reviewed documents (LEED, BREEAM, and Green Globes) as the percentage thresholds between different performance categories were averaged. As stated above, the percentage thresholds were highly consistent between the documents resulting approximately the same percentages when they averaged. The averaged percentage thresholds between the Low and Fair, Fair and Good, and Good and Excellent evaluation categories came to be 30%, 50%, and 70%, respectively. Then, using the results of generated probability distributions, the equivalent PL values at which the cumulative probabilities of occurrence became equal to each of these percentage thresholds were found as the PL thresholds between the Low, Fair, Good, and Excellent evaluation categories.

Based on the methodology explained above, the following process was applied to each of the generated probability distributions to determine the threshold PLs and, subsequently, to establish the corresponding SPS. As illustrated in Figure 6.4, the PL value at which the sum of the probabilities of occurrence for all PLs between *PL* = 0 and this PL, became 30% was determined as the PL threshold between the Low and Fair performance categories. Likewise, the PL thresholds between the Fair and Good performance categories was determined as the PL value at which the sum of probabilities of occurrence between *PL* = 0 and this PL, reached 50%. Eventually, the PL threshold between the Good and Excellent performance categories was the PL at which the cumulative probabilities of occurrence between *PL* = 0 and this PL became 70%.

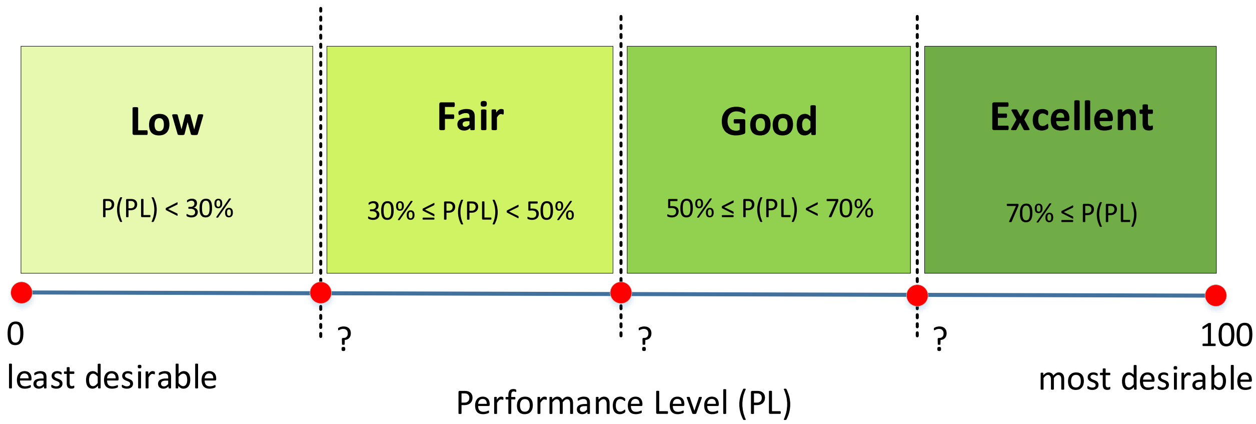

Figure 6.4 Proposed evaluation scale and PL thresholds for performance categories

The results were a set of SPSs for each SPC (Level 3), each sustainability dimension (Level 2), and for the overall sustainability (Level 1) that can be used to benchmark the performance of modular buildings at different levels.

6.2.4 Development of Decision Support Framework

By establishment of the SPSs, all the planned phases in this research for environmental and economic sustainability performance assessment of modular building were completed (see Figure 2.1 in Chapter 2 for details). Subsequently, to facilitate a holistic life cycle sustainability assessment process, all the research frameworks, methodologies, and deliverables, were incorporated into a single comprehensive sustainability assessment framework. The developed framework was proposed in the form of a multi-level decision support framework (DSF).

6.3 Sustainability Performance Scales for Environmental SPCs

As stated before, Survey C was implemented to investigate the past performance of conventional buildings in the Okanagan (and other regions in BC with the same climate zone and construction condition) with respect to all of environmental (and some of the economic) SPCs. The experts assigned the most likely PL outcome of each discrete and continuous indicator included in the survey. The data provided by the experts in each round of data collection was reviewed and revised/modified by each expert in the next round until the consensus was reached on the data at the end of the third round. This data was used to construct the probability distributions of the independent indicators correspond to each environmental SPC.

In the case of the continuous indicators, the most likely PL values were used to construct the corresponding triangular probability distributions. These distributions were then provided to the participating experts in the next round for their review. In the case of the discrete indicators, as discussed before, it was difficult for the experts to assign a probability to each and every possible PL outcomes of the indicators. In this research, the most likely PL outcome of each discrete indicator was used to estimates the probabilities of other possible outcomes. To this end, it was assumed that the probability distribution of a discrete indicator follows a discrete triangular shape. The main difference between a continuous triangular distribution and a discrete triangular distribution is in their possible outcomes. In the former distribution, the number of PL outcomes is infinite, whereas in the latter distribution, the number of PL outcomes is (countable) finite. Therefore, the rough estimate of the probability of each possible outcome in a discrete indicator can be obtained by calculating the corresponding area under the triangular curve. These rough estimate probabilities along with the corresponding rough distribution in graphical format were then provided to the participating experts for their feedback (revising or approving the proposed estimated probabilities).

To obtain the probability distribution of buildings with respect to each environmental SPCs, the methodology described earlier was followed by performing two rounds of MCS analyses. In the first round, the constructed probability distributions of the sub-SPIs related to each SPI were fed into the @Risk software as the input data along with their weights. A MCS analysis was performed separately for each SPI using the software's maximum iteration number of 100000. Consequently, the probability distribution of each SPI was generated.

As stated earlier, in some cases, there were no sub-SPIs under a SPI; therefore, the probability distributions of such SPIs had been constructed directly based on the survey results (similar to sub-SPIs). Thus, the input data of the second round of analyses were a combination of the probability distributions of SPIs generated by the first round analyses (i.e., output data) and the probability distributions of SPIs constructed directly by the survey results. In addition, the weights of the SPIs were entered. Eventually, by separately running the second round of the MCS analyses, the probability distribution of each environmental SPC was produced.

As the last step, the methodology explained to establish a SPS was applied to the generated probability distributions of the SPCs to establish the corresponding SPSs. In the following sections, the results of the data analyses and the established SPSs for the environmental SPCs have been presented.

6.3.1 SPS for Energy Performance and Efficiency Strategies

Among all the indicators determined under the EP SPC in Chapter 5, 17 indicators were independent including 6 SPIs and 11 sub-SPIs. Therefore, according to the approach adopted in this research, the questions regarding the past performances of conventional buildings with regard to these independent indicators were asked from the experts. Consequently, a probability distribution was constructed for each indicator as illustrated in Figure 6.5.

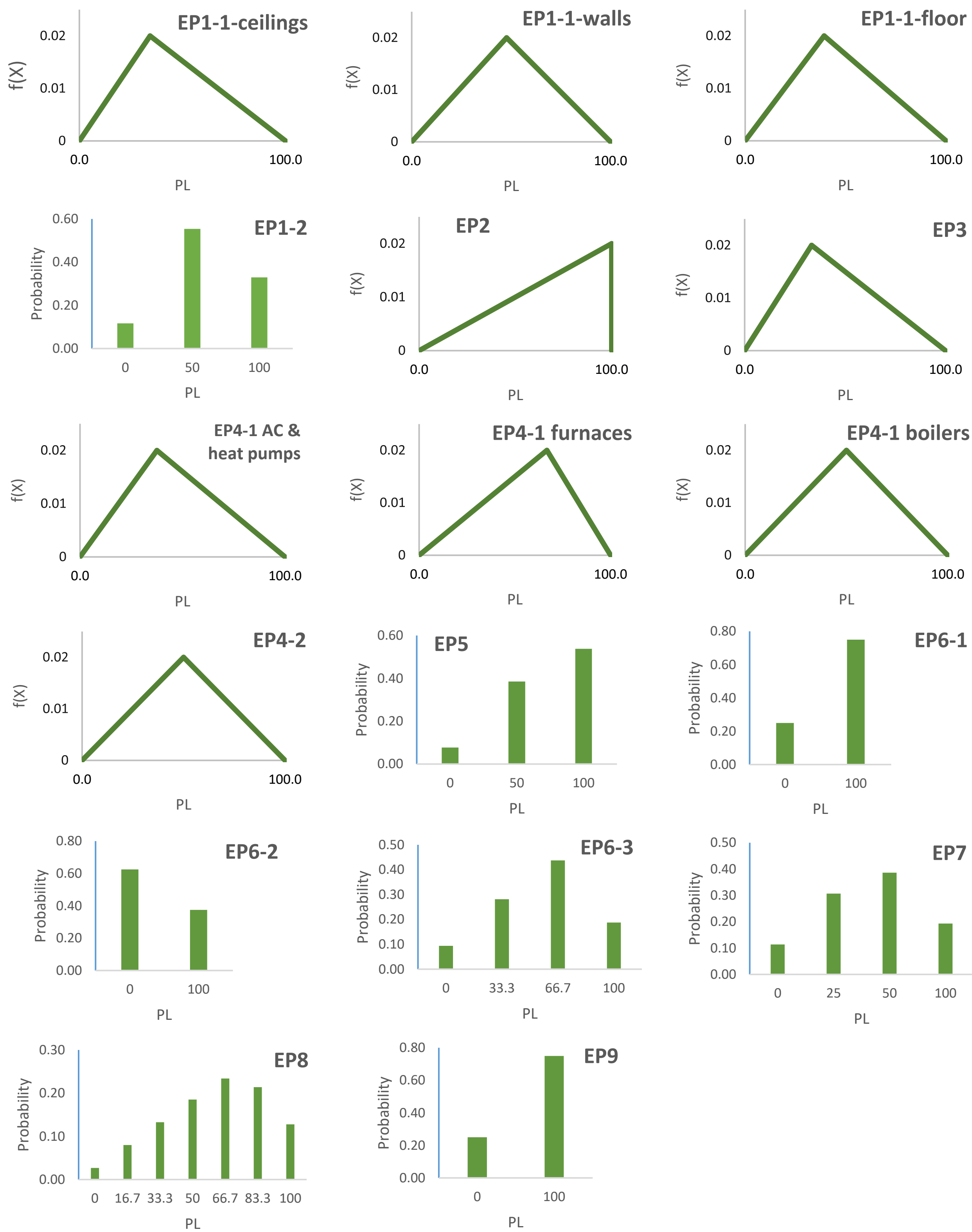

Figure 6.5 Probability distributions of the indicators under the EP SPC

The graphical form of the results of the Monte Carlo analyses for the EP SPC is presented in

Figure 6.6a, which represents the EP performance of conventional buildings. The distribution was approximately symmetric with a mean value of PL_{mean} = 57.7. The lower standard deviation (σ = 8.53) revealed that the performance of majority of buildings have been around the mean.

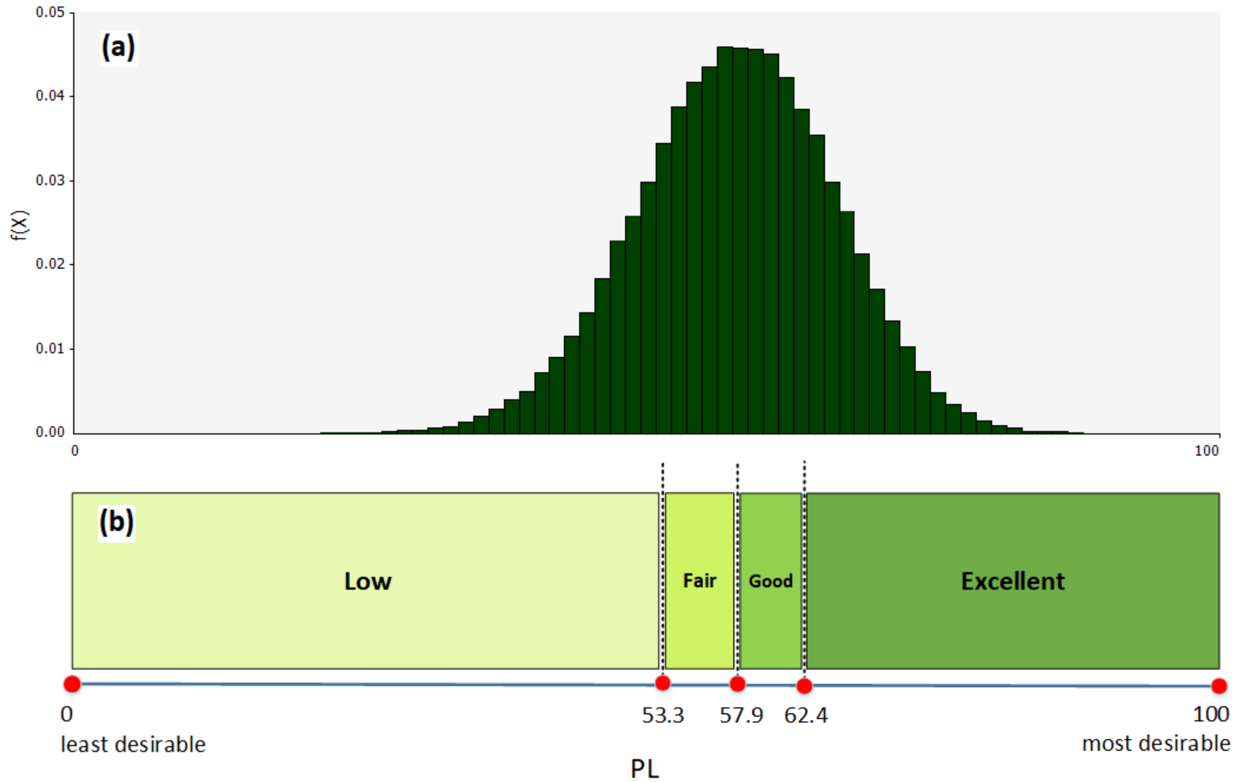

Figure 6.6 (a) Probability distribution of the EP SPC; (b) Corresponding SPS

Subsequently, the proposed evaluation scale was applied to this distribution to determine the PL thresholds correspond to the Poor, Fair, Good, and Excellent performance categories. Figure 6.6b presents the resulted SPS, which can be used for benchmarking the performance of a given building (either conventional or modular) by comparing the developing sustainability index for the EP SPC with this SPS.

6.3.2 SPS for Regional Materials

Figure 6.7 shows the constructed probability distributions for all 15 independent indicators under the RM SPC including 2 SPIs and 13 sub-SPIs. The historical performance of buildings with respect to each indicator was different. While buildings performed remarkably in the cases of some indicators (i.e., left-skewed distributions), they did not show a satisfactory performance in the cases of others (i.e., right-skewed distributions). RM4-2 was the only indicator with approximately symmetric distribution (i.e., most likely *PL* = 50).

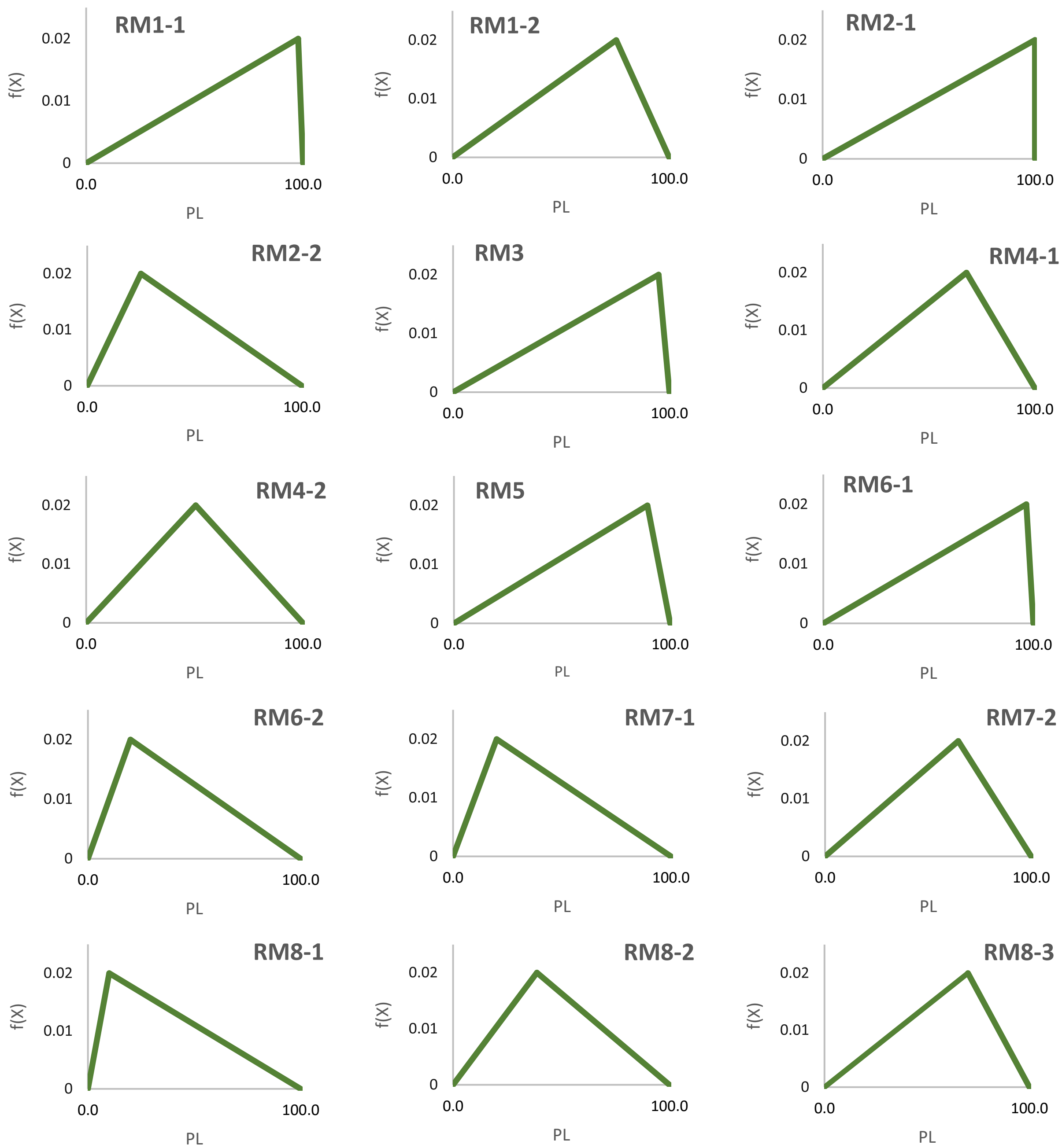

Figure 6.7 Probability distributions of the indicators under the RM SPC

By conducting the MCS analyses, the behavior of buildings with regard to the use of regional materials was simulated as demonstrated in Figure 6.8a. Because there was a balance between the number of left-skewed and right-skewed distributions of the contributing indicators, a centrally symmetric distribution was anticipated for the generated distribution of the RM SPC.

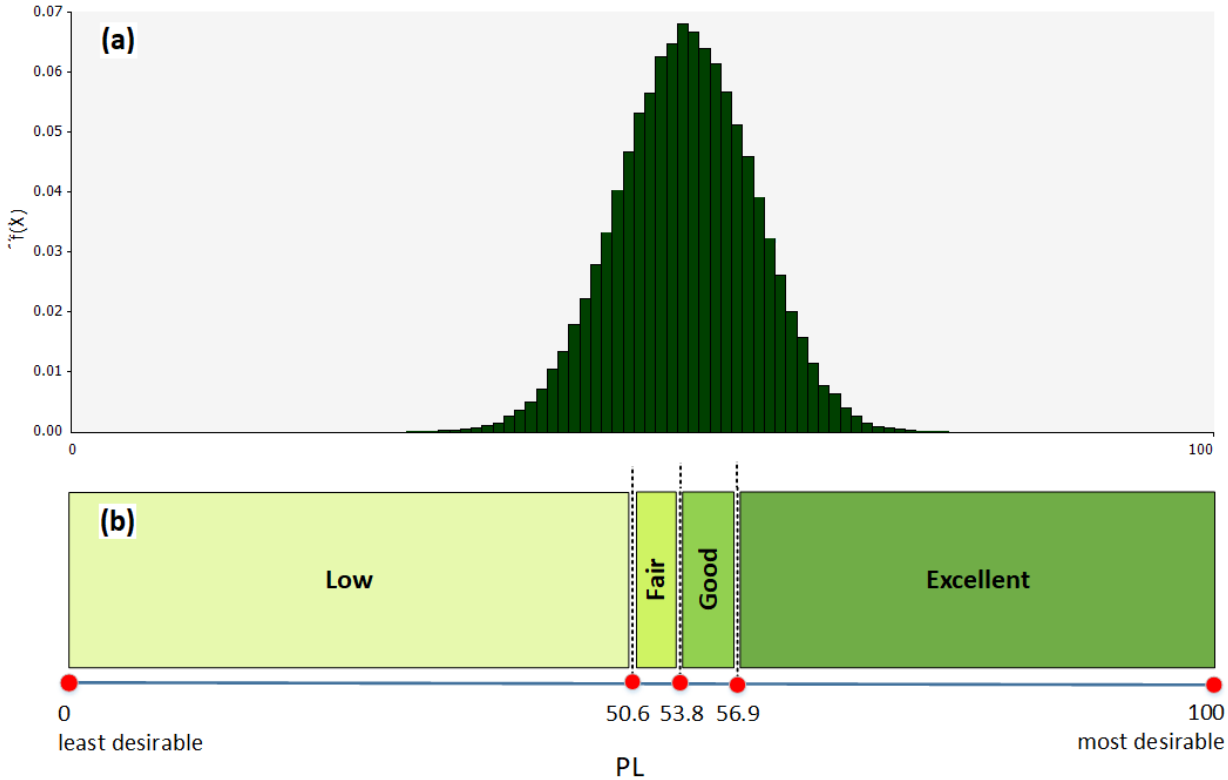

Figure 6.8 (a) Probability distribution of the RM SPC; (b) Corresponding SPS

By applying the proposed evaluation scale, the corresponding SPS for this SPC was established as shown in Figure 6.8b. The lower standard deviation of σ = 5.9 indicated that the RM performance of most of the buildings in BC have been around the mean.

6.3.3 SPS for Construction Waste Management

The CWM SPC included two SPIs, one of them was independent and the other one consisted of two sub-SPIs. The constructed probability distributions for the independent indicators were constructed based on the experts' opinions as exhibited in Figure 6.9.

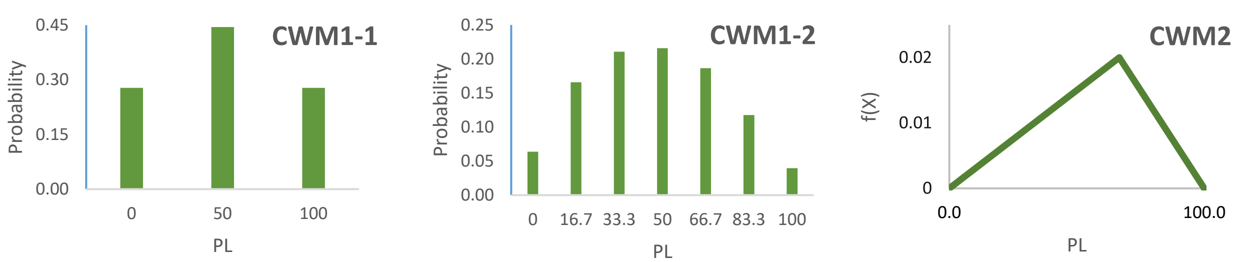

Figure 6.9 Probability distributions of the indicators under the CWM SPC

Figure 6.10 shows the historical behaviour of conventional buildings in terms of waste management as well as the corresponding SPS.

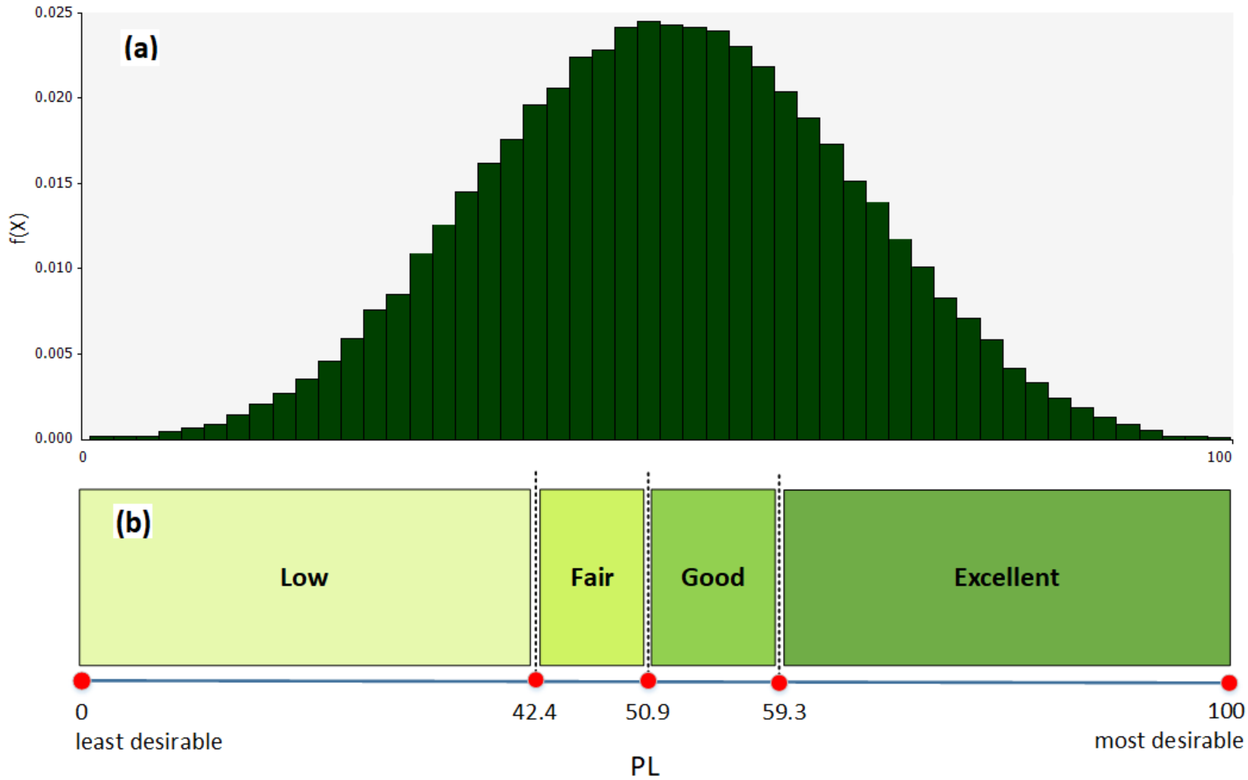

Figure 6.10 (a) Probability distribution of the CWM SPC; (b) Corresponding SPS

Through the first round of simulation analyses, the probability distribution of the dependent SPI (CWM1) was obtained. Then, through the second round, the probability distribution of the parent CWM SPC was generated by combing the distributions of the two SPIs (Figure 6.10a). The resulted distribution was approximately a normal distribution. Dissimilar to the distribution for the RM SPI, higher standard deviation in this distribution ($\sigma = 15.6$) indicated that the single-family building projects performed differently in terms of waste management by covering all the possible PLs. This was also confirmed by the developed SPS (Figure 6.10b) where the PL intervals associated with the central performance categories (i.e., Fair and Good) were wider compared to the cases of EP and RM SPCs above.

6.3.4 SPS for Renewable and Environmentally Preferable Products

As demonstrated in Figure 6.11, all the probability distributions of all 15 independent indicators under the REP SPC were right-skewed (i.e., the most likely PL < 50). This indicated the limited application of renewable and environmentally friendly materials (e.g., recycled materials) in different components of single-family buildings. According to the experts in this research, most of the building projects in BC still utilize fewer environmentally responsible materials such as recycled, reclaimed, and FSC-certified.

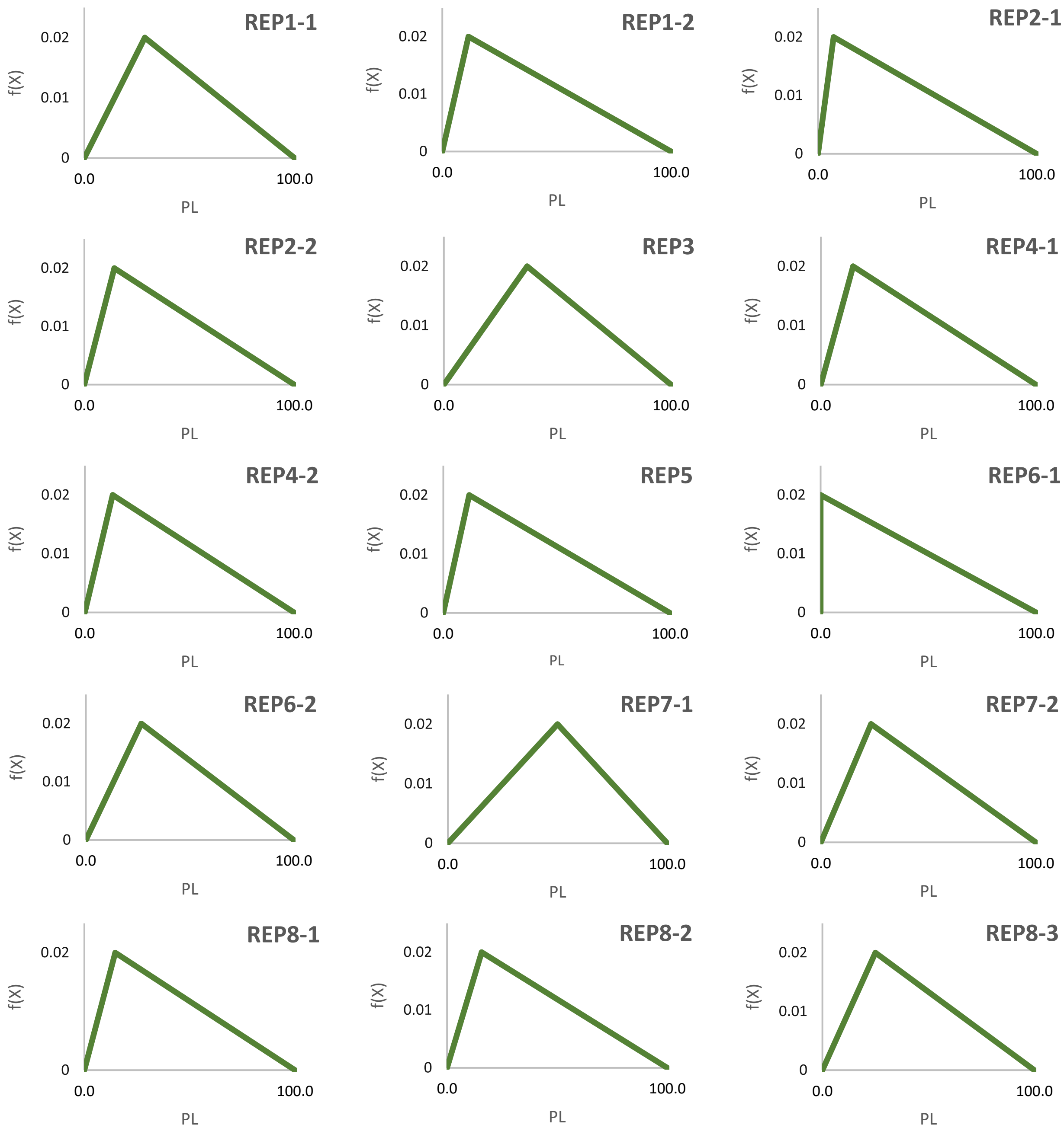

Figure 6.11 Probability distributions of the indicators under the REP SPC

The probability distribution of the REP SPC and the corresponding proposed SPS are presented in Figure 6.12. The average PL value of 40 supported the above discussion. On the positive side, this provides a vast opportunity to improve the REP performance of a new building project by using more environmentally responsible materials, which can also lead to improvement of its overall sustainability performance.

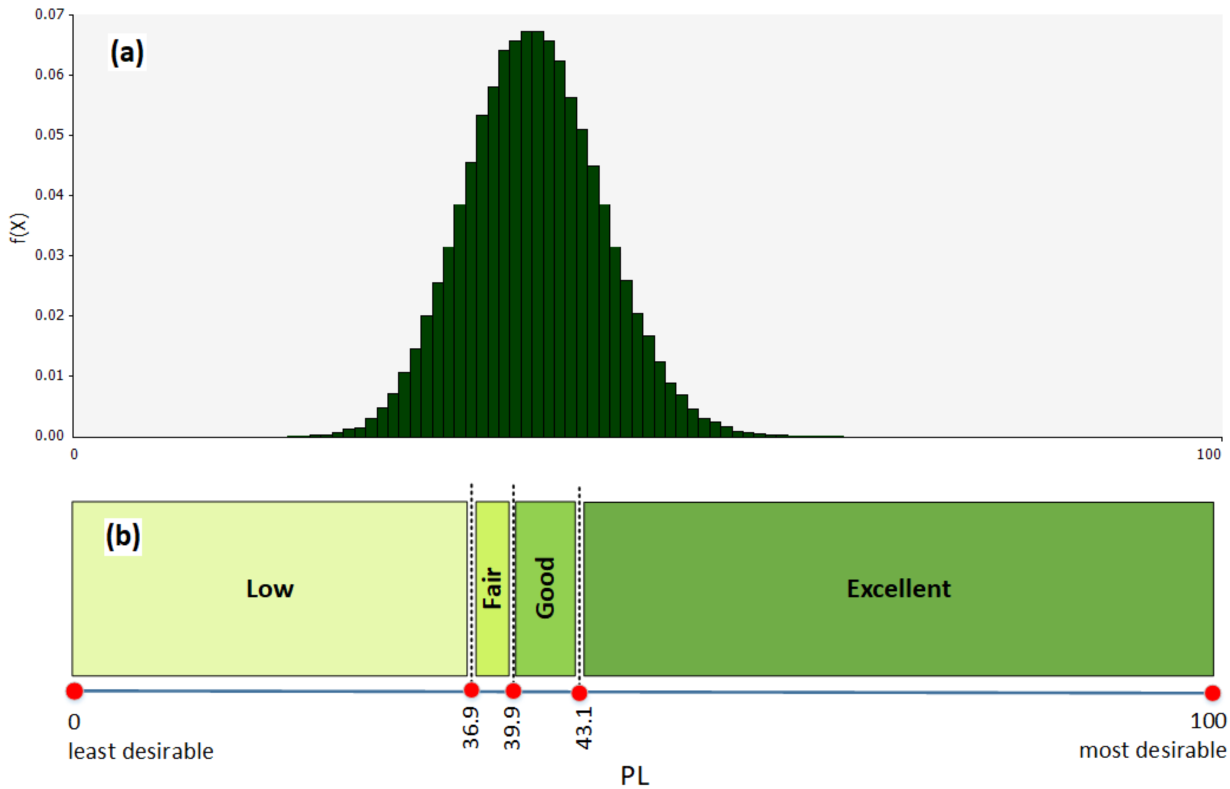

Figure 6.12 (a) Probability distribution of the REP SPC; (b) Corresponding SPS

As illustrated in the proposed SPS (Figure 6.12b), if a building's sustainability index for this SPC reaches as low as *PL* = 36.9, it will show moderate performance which can quickly reach the Good performance and even Excellent performance by a small improvement in its performance. This is remarkable especially when comparing this SPS with the SPSs proposed for some other SPCs. For example, the PL threshold between the Good and Excellent performance categories (*PL* = 43.1) for the REP SPC, was even less than the PL threshold between the Poor and Fair performance categories for the RM SPC (*PL* = 50.6).

6.3.5 SPS for Site Disruption and Appropriate Strategies

The SD SPC is one the environmental SPCs that its independent indicators are mostly discrete meaning that the number of possible PL outcomes is finite (countable). Figure 6.13 shows the constructed probability distributions for the nine indicators under this SPC. It can be observed fro the distributions that the performances of single-family buildings projects on the project site with respect to different aspects of 'site disruption' have not followed the same trend. In the cases of some indicators, such as SD2-2 and SD4-2, buildings historically showed better performance compared to some other indicators such as SD3.

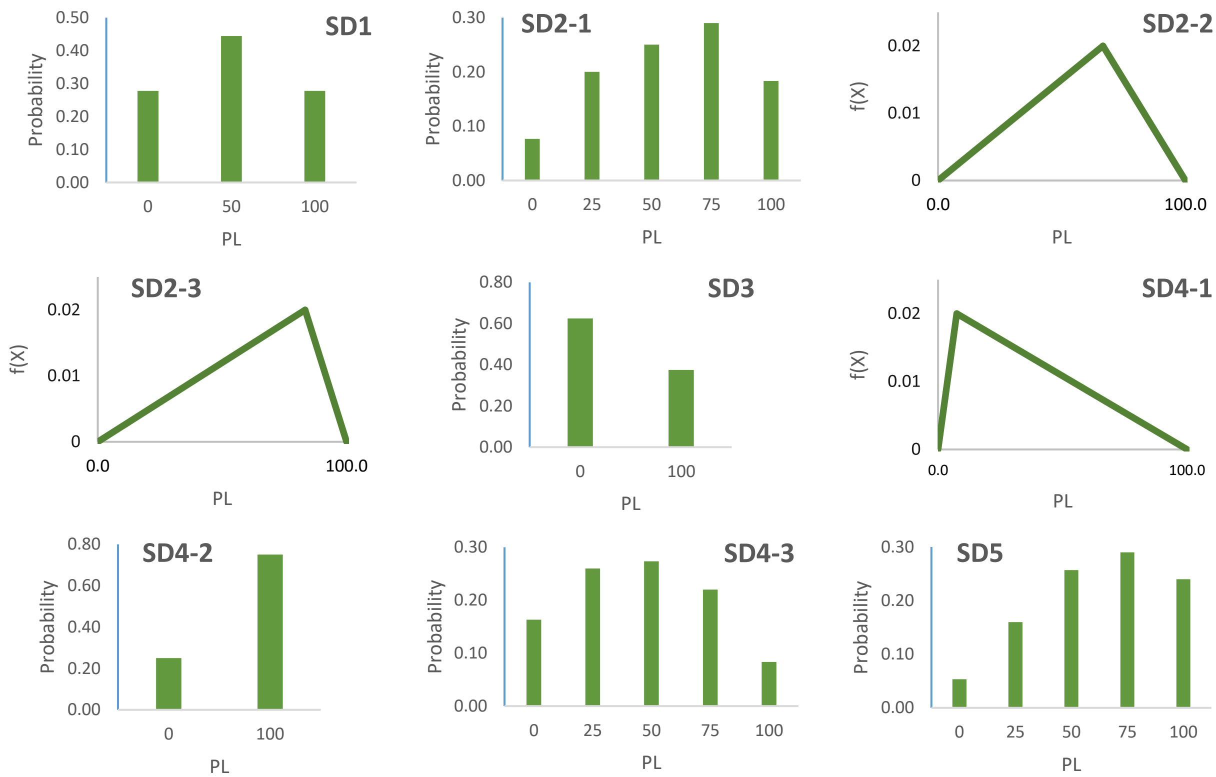

Figure 6.13 Probability distributions of the indicators under the SD SPC

Figure 6.14a illustrates the performance of buildings with respect to the SD SPC. The distribution is a centrally symmetric distribution (PL_{mean} = 49.9) with a relatively high standard deviation. The proposed SPS for benchmarking the SD performance of a building (either conventional or modular) is presented in Figure 6.14b.

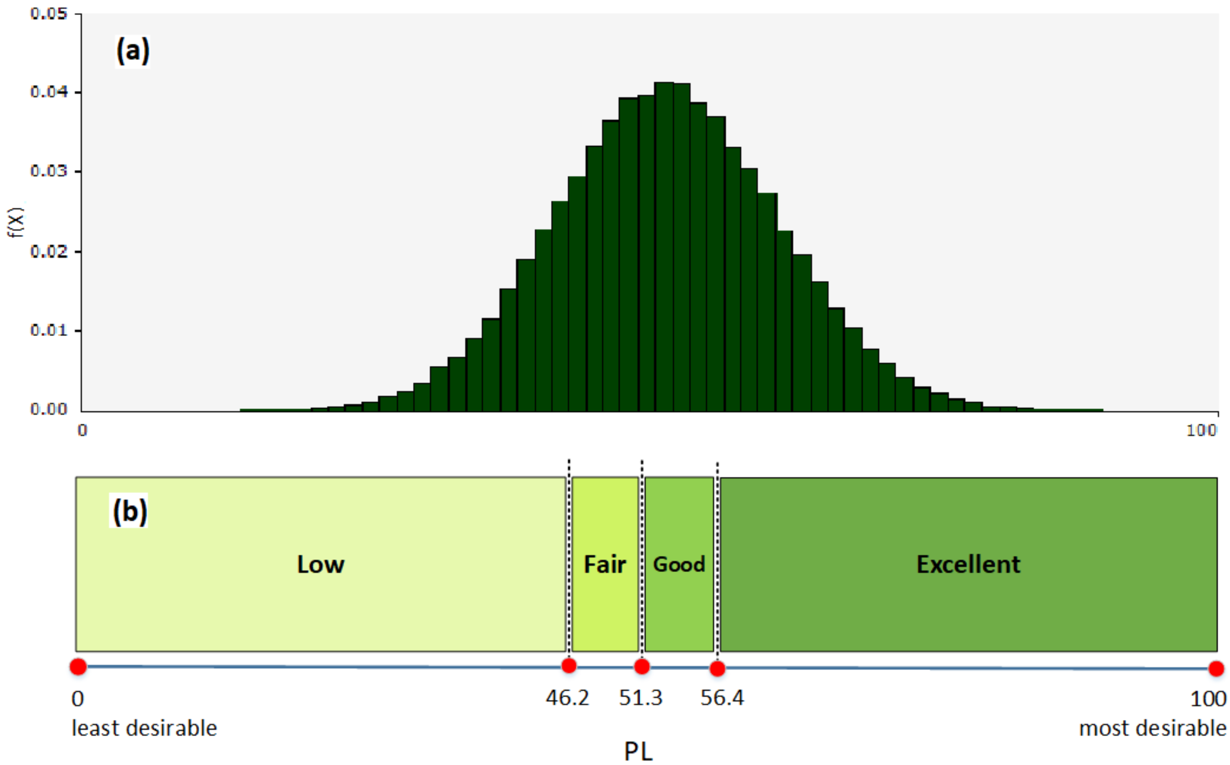

Figure 6.14 (a) Probability distribution of the SD SPC; (b) Corresponding SPS

6.3.6 SPS for Renewable Energy Use

Despite many environmental and economic benefits offered by the use of renewable energy sources, it does not still account for a considerable portion of buildings' energy needs. As discussed earlier, three SPIs were determined under the RE SPC. All of these SPIs were independent indicator. Therefore, the performances of buildings with respect to these SPIs were asked directly from experts. The collected data via Survey C showed that the residential buildings have not replaced a significant portion of the required energy for electricity, space heating, and water heating by renewable energy sources of any kind as indicated by the corresponding probability distributions in Figure 6.15.

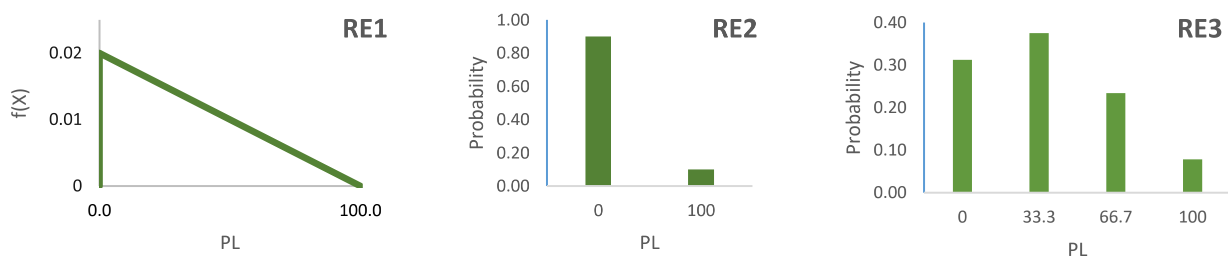

Figure 6.15 Probability distributions of the indicators under the RE SPC

The results of MCS analyses on the above distributions discovered that the RE performance of buildings is at the bottom of the environmental SPC category (and even within the economic category). As shown in Figure 6.16a, the probability distribution of RE is a right-skewed curve with the lower average PL of 30.7. The corresponding SPS is presented in Figure 6.16b.

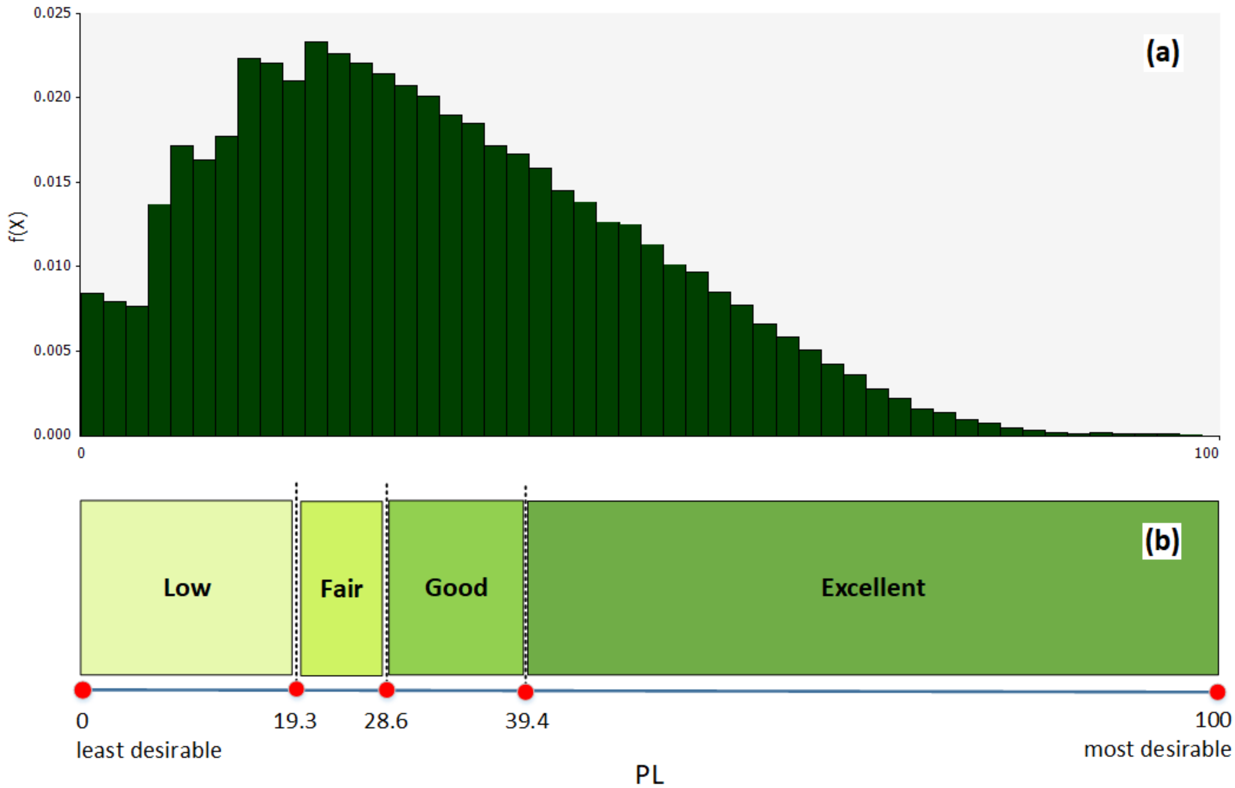

Figure 6.16 (a) Probability distribution of the RE SPC; (b) Corresponding SPS

6.3.7 SPS for Greenhouse Gas Emissions

As discussed before, the literature review did not present any LCA studies that investigated the GHG impacts due to construction of single-family buildings in the Okanagan and broader in BC. The other data source to obtain such information was to enquire the expert opinions. However, in order to provide appropriate and accurate answers to the related questions, the experts should have performed LCA analyses on real projects. As anticipated, such analyses had not been performed and reported by any construction firms in BC as already confirmed by the literature review. Therefore, it was not possible to discover the historical performances of buildings with respect to the GE SPC and construct the corresponding probability distribution and SPS. This is why a different methodology for performance assessment of modular buildings with respect to the GE SPC was adopted in this research. As discussed earlier, the performance assessment of modular buildings has been based on conducting the LCA analyses of case study buildings (including modular and conventional), developing a set of environmental impact indices, and comparing these indices between these buildings. In other words, the environmental impacts due to construction of a modular building is compared with the environmental impacts due to construction of other similar modular and conventional buildings. This method of benchmarking is called ‘review benchmarking’ method (Stapenhurst 2009). In contrast, in the cases of all other SPCs, the performance of a modular building has been evaluated by comparing the developed sustainability indices with the established SPSs (i.e., the historical performance of similar conventional buildings).

The details of the data collection process for LCA studies to address the GE SPC have been described in Chapter 7 where the case study analyses were performed.

6.4 Sustainability Performance Scales for Economic SPCs

Similar to the environmental SPCs, the experts’ feedback was used for construction of suitable probability distributions of the independent indicators under the economic SPCs. As stated before, some of the economic SPCs are more and some are less locality sensitive criteria. Therefore, the data related to the performance of buildings with respect to the indicators associated with the former SPCs and latter SPCs was collected separately using Survey B and Survey C, respectively.

The same methodology followed to conduct the MCS analyses, develop the probability distributions, and establish SPSs for the environmental SPCs was used in the case of the economic SPCs. Therefore, the detailed descriptions of the methodology are not repeated in this section and only the results are presented and discussed.

6.4.1 SPS for Integrated Management

The IM SPC included three SPIs each of them consisted of a number of sub-SPIs. Therefore, the independent indicators were only the sub-SPIs for which the data of the historical performance of single-family buildings was collected and the corresponding probability distributions were constructed. Because all sub-SPIs are discrete variables, the values on the y-axis of the probability distributions of a sub-SPI indicates the probabilities of its possible PL outcomes (Figure 6.17).

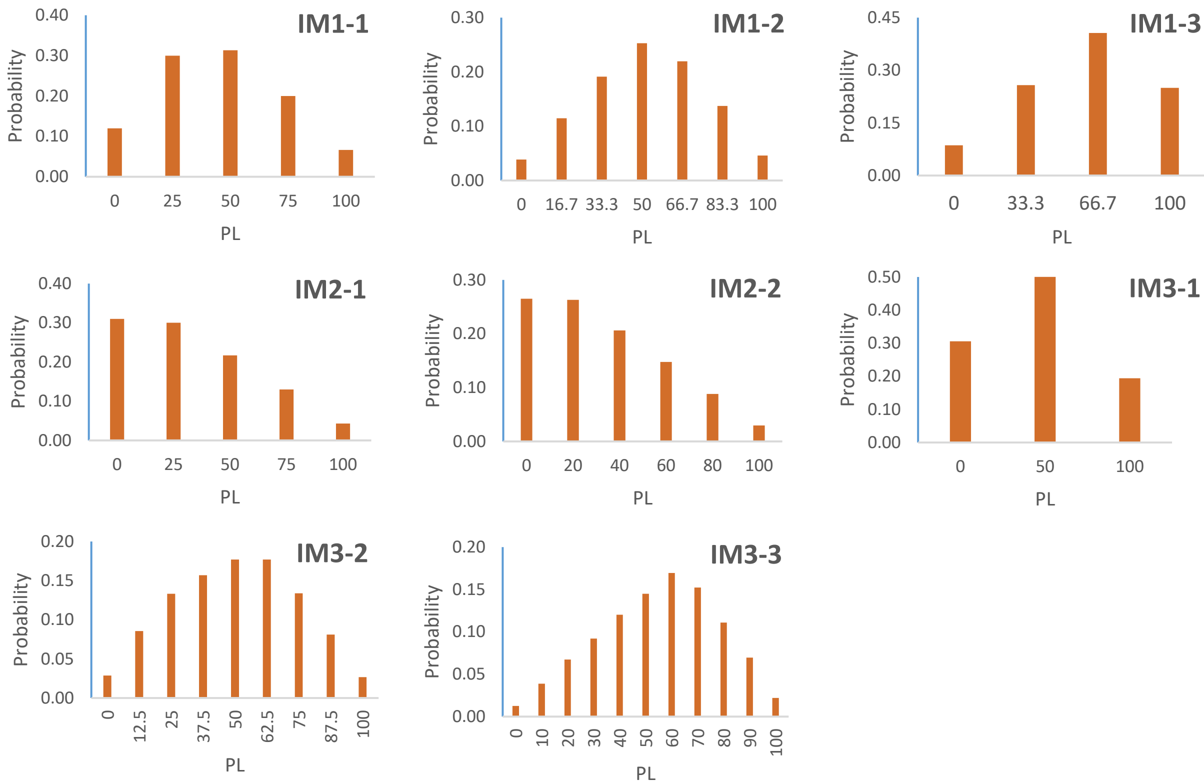

Figure 6.17 Probability distributions of the indicators under the IM SPC

Figure 6.18a illustrates the results of the final round of the simulation analyses for the probability distribution of the performance of buildings related to the IM SPC. The distribution is approximately normal and centralized (PL_{mean} = 45.9). Using the proposed evaluation scale discussed in the methodology section, the PL threshold values for different evaluation categories were determined and the SPS for benchmarking the IM performance of buildings was established (Figure 6.18b).

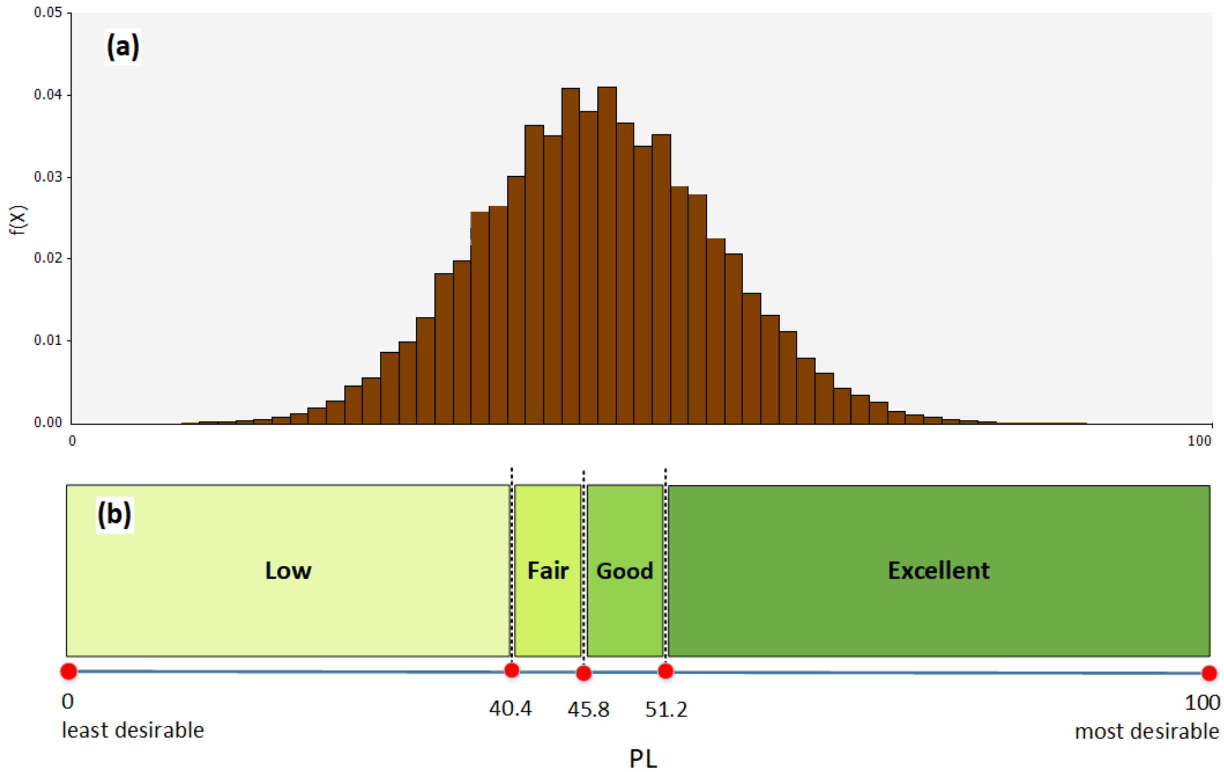

Figure 6.18 (a) Probability distribution of the IM SPC; (b) Corresponding SPS

6.4.2 SPS for Durability of Building

The durability feature in a building can offer both environmental and economic advantages. The environmental benefit of durability is mainly the less demand for repairs and renovation of existing buildings and also construction of new buildings which result in resource efficiency. However, as stated before, resource efficiency has already been considered within the environmental SPCs. Therefore, the DB SPC was included under the economic category to address the economic benefit of durability. The past performance of single-family buildings with regard to durability indicators have been demonstrated in Figure 6.19.

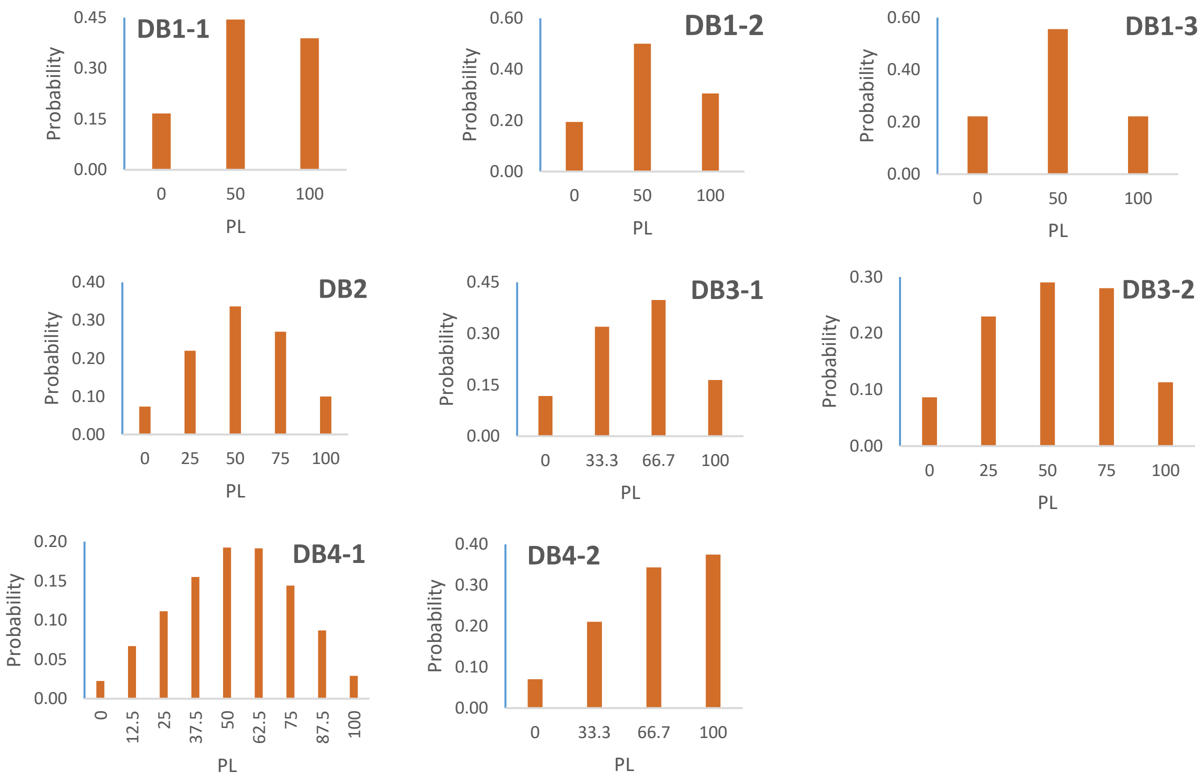

Figure 6.19 Probability distributions of the indicators under the DB SPC

A few rounds of MCS analyses were performed by using the above distributions as the input of analyses to discover the historical performance of buildings in terms of durability (Figure 6.20a). Because all the contributing indicators have been discrete variables, the number of possible PL outcomes of the parent DB SPC was also finite. This is why not all the PLs between 0 and 100 have been among the possible outcomes of this SPC as shown in Figure 6.20a.

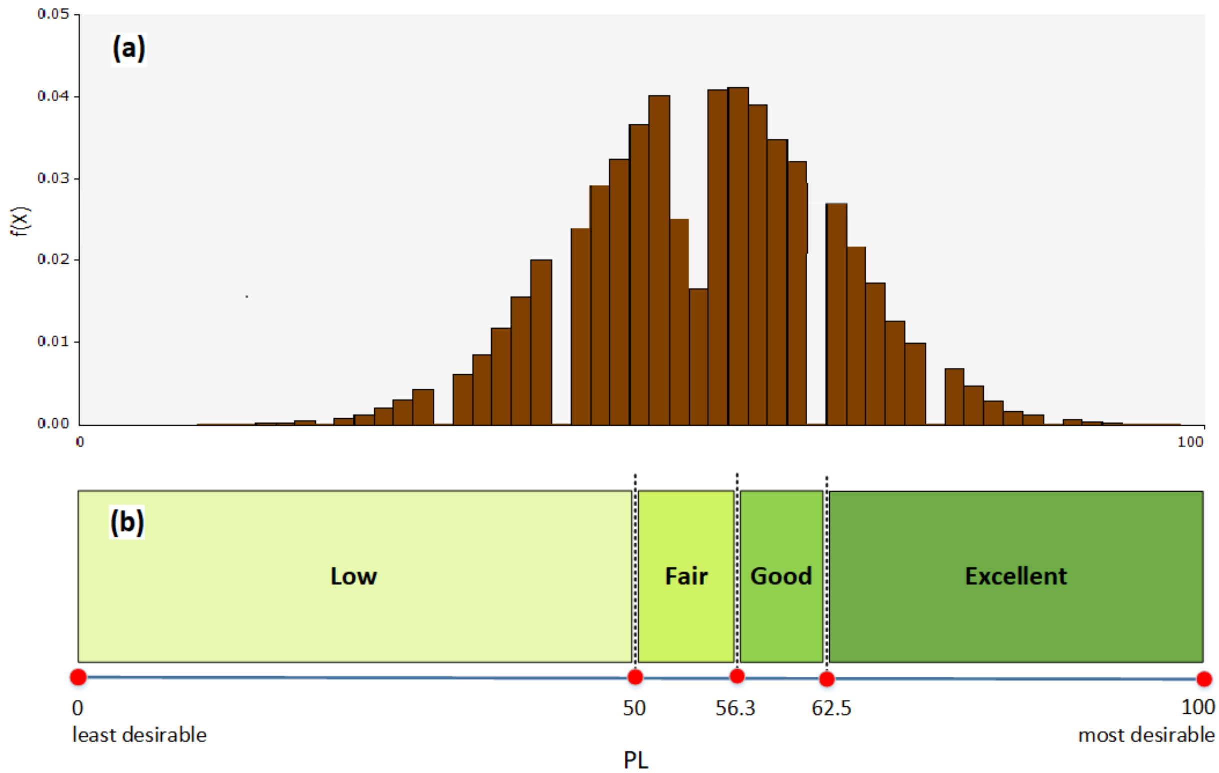

Figure 6.20 (a) Probability distribution of the DB SPC; (b) Corresponding SPS

Figure 6.20b presents the developed SPS for this SPC. It can be observed that the Fair performance category started at PL = 50, which is a relatively high threshold. This means that majority of the single-family conventional buildings in BC have considered and implemented suitable durability strategies in the design stage such that the PL of the DB SPC for a new building design should be at least 50 in order for the building to perform Fair.

6.4.3 SPS for Adaptability of Building

As discussed in Chapter 5, adaptability of buildings, in particular residential low-rise buildings, is one of the criteria that has not been widely addressed in the literature. In an attempt to investigate the adaptability performance of single-family buildings and establish the corresponding benchmarks, this research determined three relevant SPIs, which can serve as a basis for future research. Similar to the IM SPC above, all the SPIs and sub-SPIs under the AB SPC are discrete; therefore, the corresponding probability distributions are discrete. The constructed probability distributions for the independent indicators are illustrated in Figure 6.21. From these distributions, it can be concluded that the single-family buildings in BC have not shown a high level of adaptability. This was anticipated because (1) adaptability requires additional costs in the design and construction of buildings; (2) the necessity and benefits of adaptability that can offset the extra costs have not still been documented and well understood. It should also be stressed that, not all the building projects, in particular residential buildings, require high level of adaptability. However, this is an additional economic value if a building has be prepared to accommodate future changes that can be either the users' needs or technological changes.

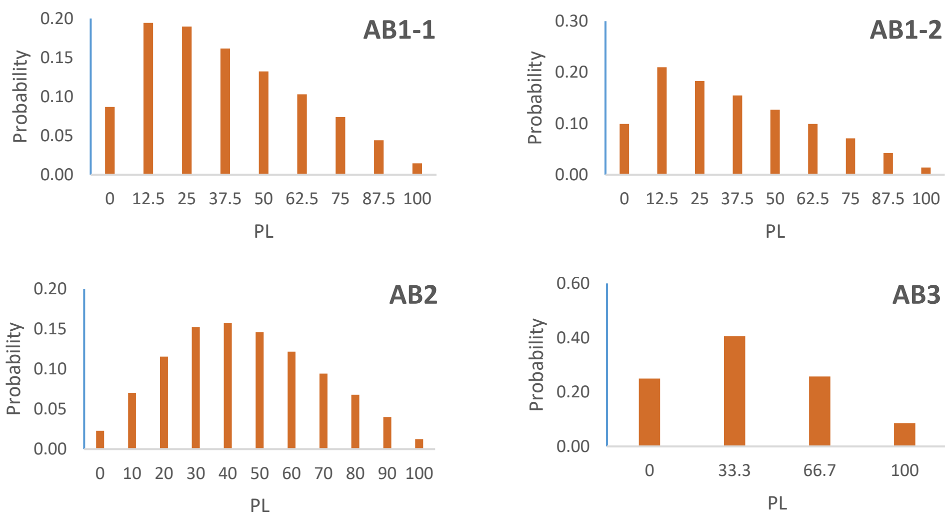

Figure 6.21 Probability distributions of the indicators under the AB SPC

The performance of single-family buildings with respect to the IM SPC has been simulated by combining the probability distributions of the associated SPIs as shown in Figure 6.22a. This is a right-skewed distribution that indicates lower performance of buildings with respect to adaptability compared to the above-discussed economic SPCs. This can also be concluded from the developed SPS for this SPC (Figure 6.22b). However, on the positive side, a new building (either modular or conventional) can show higher AB performance easier that other SPCs by incorporating a number of adaptability measures discussed before into its design. As demonstrated in the established SPS, the PL threshold between the Low and Fair was as low as PL = 32.5. Even a PL value close to 50 (PL = 47.8) represents the Excellent adaptability performance of a building.

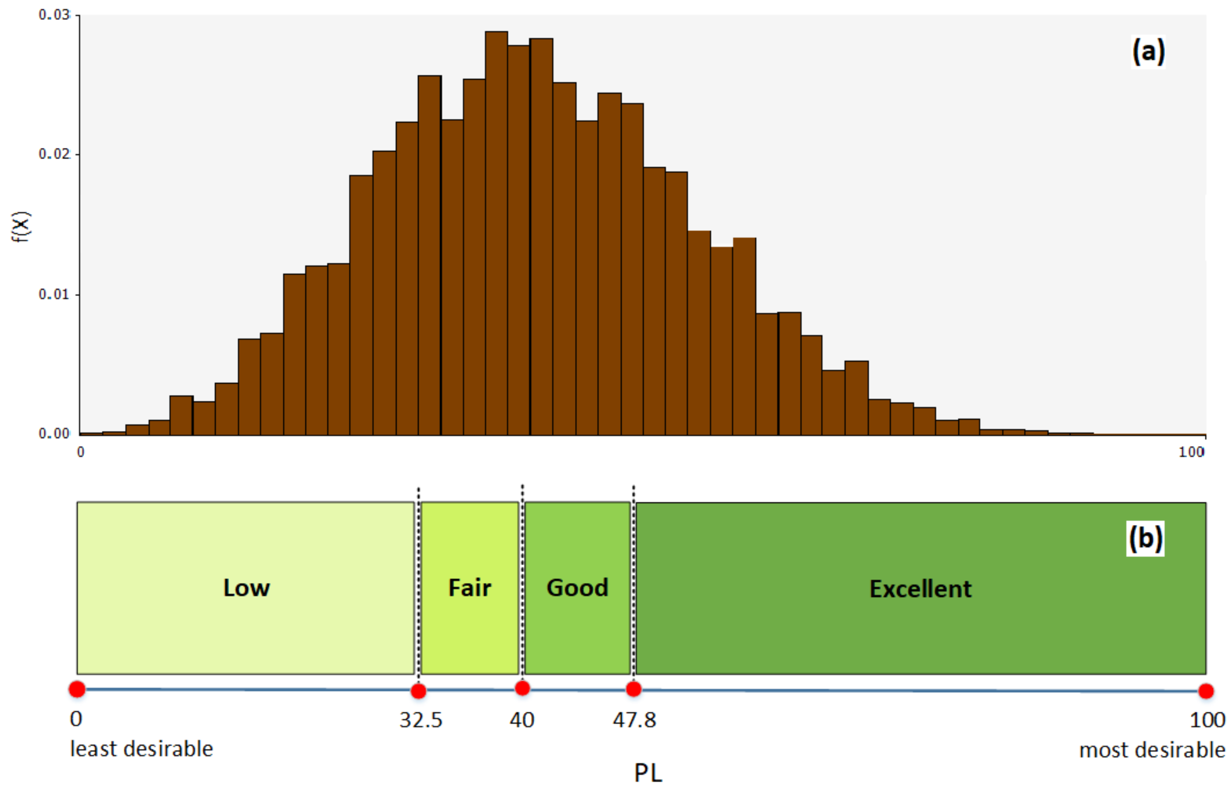

Figure 6.22 (a) Probability distribution of AB SPC; (b) Corresponding SPS

6.4.4 SPS for Design and Construction Time

Unlike to the IM, DB, and AB SPCs, the remaining economic SPCs in this research, i.e., DCT, DCC, OC, MC, and IRR, are highly sensitive to the local construction conditions. Hence, the data related to the historical performances of buildings with respect to these SPCs was collected based on local experts in the Okanagan, BC (Survey B). The results of data analyses have been provided in the following sections.

As reported in Chapter 4, the duration of a building project was located on top of the economic criteria by the construction practitioners, which indicated the vital role of the DCT SPC in the economy of the project (i.e., time is money). Using the collected information, the triangular distributions of the design time (DCT1) and the construction time (DCT2) were produced as illustrated in Figure 6.23. The distribution of the DCT1 SPI shows that most of the single-family buildings have been designed longer than the average applicable time range (i.e., most likely $PL_{DCT1} < 50$). On the contrary, the buildings showed better performance in terms of the construction duration (i.e., most likely $PL_{DCT2} > 50$).

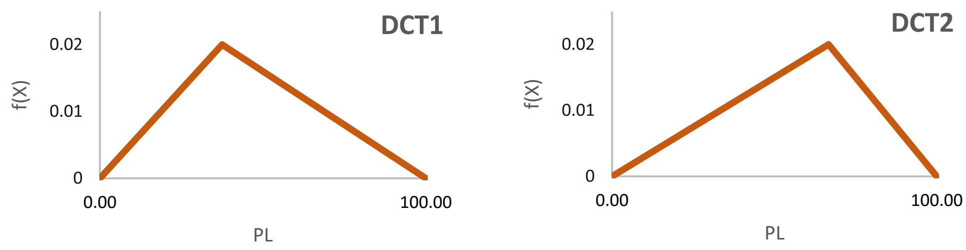

Figure 6.23 Probability distributions of the indicators under the DCT SPC

Figure 6.24a shows the probability distribution of the DCT SPC. It should be mentioned that, although the distributions of the contributing SPIs were symmetrically balanced (one is right-skewed and the other is left-skewed), the resulted distribution for the parent SPC was not symmetric. This was because of the difference in the applied weights for the DCT1 and DCT2 when performing MCS analyses, which was significantly higher for DCT2. For example, a simple mistake in any of the construction activities can delay the project comparable with the total design time.

The proposed SPS for this SPC is presented in Figure 6.24b. Compared to the previously discussed SPCs, the PL threshold values for different performance categories have moved ahead. This means that the conventional building projects in the Okanagan, performed relatively fast in terms of the design and construction duration. Therefore, a new building project should be on time enough to be evaluated Good or Excellent. In addition, because of higher standard deviation in the probability distribution of the SPC, each of the performance categories included a wider range of possible PLs.

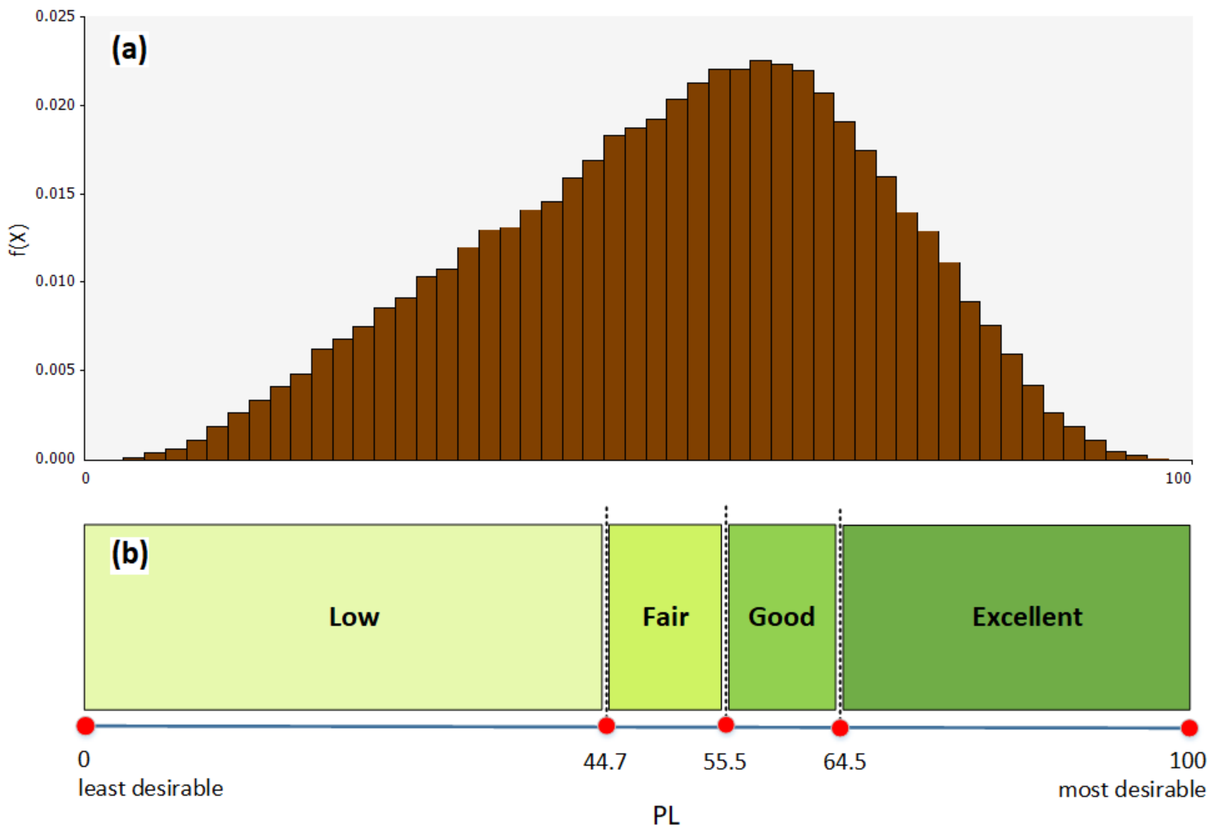

Figure 6.24 (a) Probability distribution of the DCT SPC; (b) Corresponding SPS

6.4.5 SPS for Design and Construction Costs

Similar to the duration of building projects, the costs associated with the design and construction phase can contribute significantly to the projects' economy. As reported earlier, the DCC ranked second within the economic SPC category. Based on the participating experts' opinions (Survey B), the cost performances of single-family building projects in the Okanagan have been identified and translated into suitable probability distributions for the DCC1 and DCC2 SPIs (Figure 6.25). From these distributions, it can be observed that majority of the building projects have been designed with the cost close to the average design cost. However, the construction cost for most of the projects has been cheaper than the average cost.

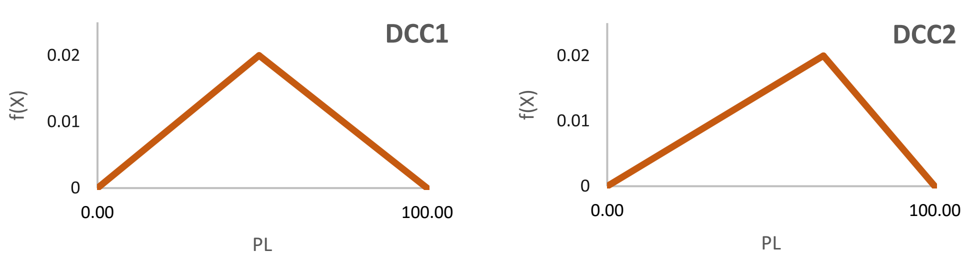

Figure 6.25 Probability distributions of the indicators under the DCC SPC

Aggregation of the above distributions resulted in the distribution of the parent DCC as presented in Figure 6.26a. This distribution is left-skewed indicating high performance of buildings in terms of overall design and construction costs. Using this distribution and the proposed evaluation scale discussed in the methodology section, the corresponding SPS was established (Figure 6.26b). The SPS shows relatively higher PL thresholds for the performance categories. For example, in order for a project to perform excellent, its performance should be at least PL = 67.5 which is a high threshold compared to all Excellent thresholds in other SPSs.

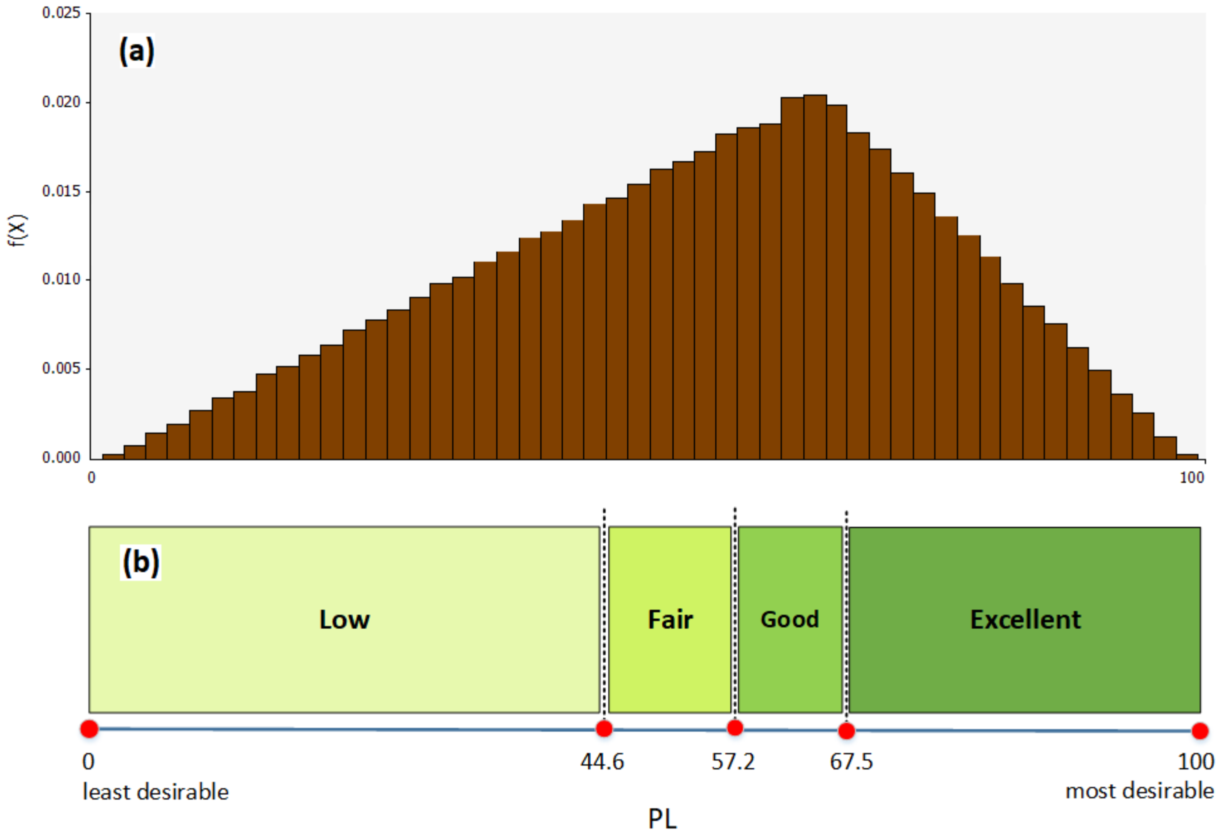

Figure 6.26 (a) Probability distribution of the DCC SPC; (b) Corresponding SPS

6.4.6 SPS for Operational Costs

As mentioned in Chapter 5, this SPC comprised only one SPI, which is the running costs (OC1). Therefore, the performance of buildings with respect to operational costs was determined based of their performance with respect to running costs. The results of the survey in the form of the probability distribution is presented in Figure 6.27a. The OC distribution is slightly left-skewed indicating that operational costs in many of the single-family buildings in the Okanagan have been less than the average costs (i.e., most likely $PL_{OC} > 50$). The corresponding SPS for benchmarking the new building projects has been presented in Figure 6.27b.

Figure 6.27 (a) Probability distribution of the OC SPC; (b) Corresponding SPS

6.4.7 SPS for Maintenance Costs

Similar to the OC SPC, the MC SPC consisted of only one SPI (MC1). Thus, the probability distribution of MC followed the same as the probability distribution of the MC1 SPI (i.e., repair and replacement costs) as illustrated in Figure 6.28a. It can be observed from the constructed distribution that the performance of buildings in the Okanagan with respect to maintenance costs follow a symmetric pattern (PL_{mean} = 50.4).

The corresponding SPS for benchmarking the MC performance of a building was established and presented in Figure 6.28b. Comparison of the SPSs proposed for the OC and MC SPCs revealed that the PL thresholds for different performance category in the latter SPS were marginally less than the corresponding PL thresholds in the former SPS. This is because, according to the experts, single-family buildings showed slightly higher performances in terms of the operational costs.

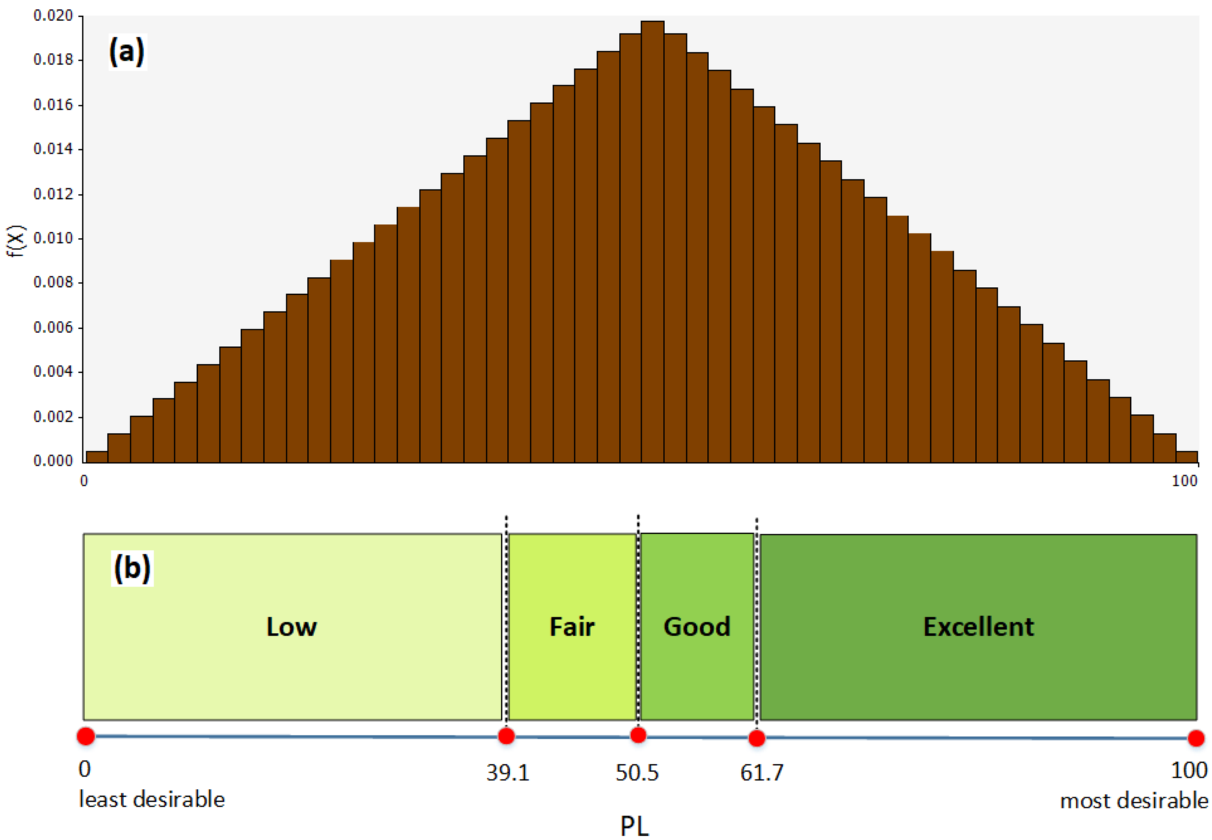

Figure 6.28 (a) Probability distribution of the MC SPC; (b) Corresponding SPS

6.4.8 SPS for Investment and Related Risks

In addition to the OC and MC SPC, the IRR SPC also comprised one SPI, i.e., IRR1. Therefore, the probability distribution of this SPC was the same as its single SPI. As detailed in Chapter 5, the PLF for the IRR1 SPI included three data variables. The number of data variables of different PLFs is not important; however, it is important to note that each of these three data variables in the PLF of the IRR1 SPI has itself been a SPI. In other words, these SPIs now play the roles of data variables in the PLF of IRR1. According to Chapter 5, the three data variables of this SPI were DCC1, DCC2, and SP. DCC1and DCC2 have been the SPIs under the 'design and construction (DCC)' SPC. In addition, SP is the sale price of the finished single-family buildings. The probability distributions of DCC1 and DCC2 have been constructed and presented earlier in the related section (see Figure 6.25). Similarly, the probability distribution for SP was constructed based on the experts' opinions. This distribution along with the repetition of the distributions of DCC1 and DCC2 are shown in Figure 6.29.

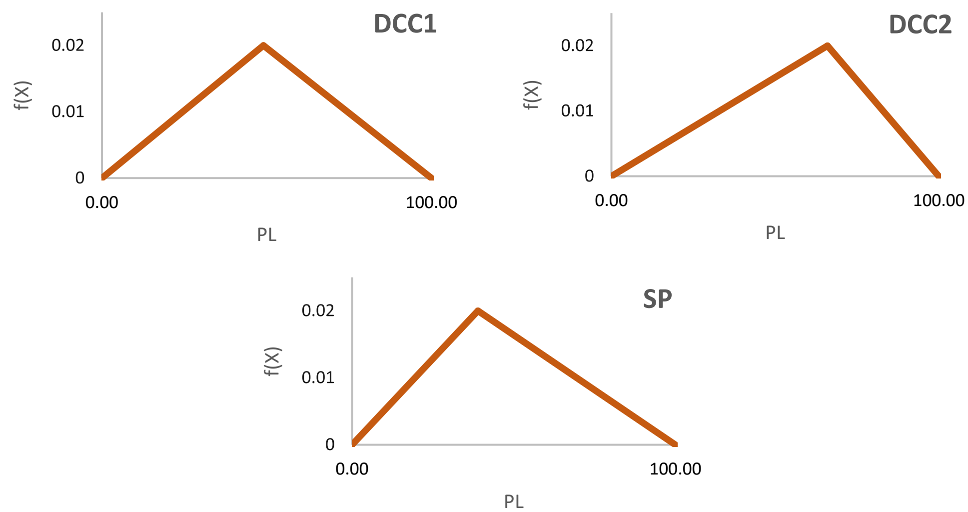

Figure 6.29 Probability distributions of the indicators under the IRR SPC

These distributions were fed into the simulation software as the input data to generate the distribution of the IRR SPC as presented in Figure 6.30a. The resulted distribution was a centralized symmetric distribution.

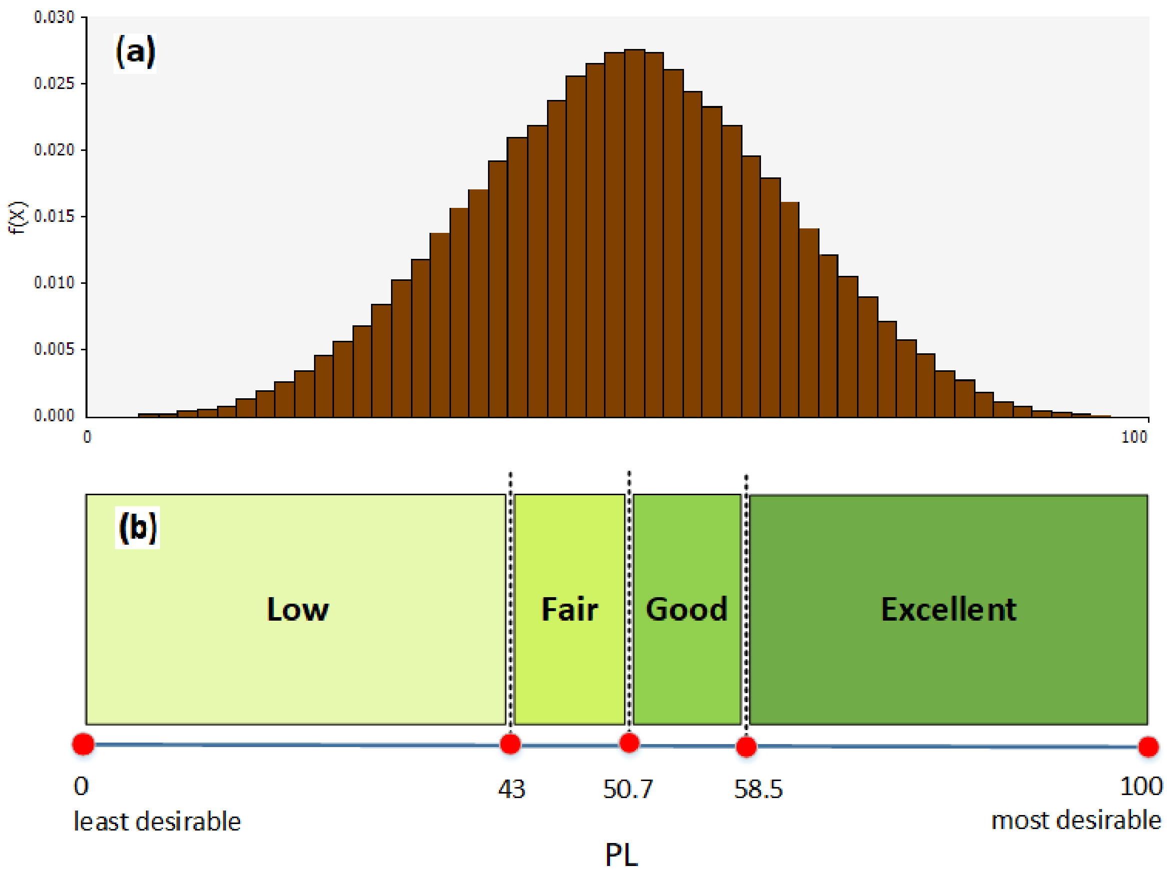

Figure 6.30 (a) Probability distribution of the IRR SPC; (b) Corresponding SPS

Using the proposed evaluation scale, a SPS for benchmarking the performances of single-family buildings with respect to profitability of the project was established (Figure 6.30b). The SPS was an approximately symmetric scale as anticipated from the probability distribution of IRR. For example, the upper limit for the Low performance category (PL = 43) and the lower limit for the Excellent performance category (PL = 58.5) were nearly symmetric.

6.5 Sustainability Performance Scales for Sustainability Dimensions

In the previous sections, the historical performances of single-family buildings in BC (with the focus on the Okanagan) with regard to each environmental and economic SPC were explored and the corresponding SPSs were established for performance benchmarking at Level 3 (i.e., SPC level). In the present section, similar methodology was used to identify the past performance of these buildings with respect to each of the environmental and economic dimensions and establish the corresponding SPSs at Level 2. To this end, the probability distributions of the SPCs along with their importance weights were combined by performing the MCS analyses to produce the probability distributions of the environmental and economic performances of buildings.

Figure 6.31a exhibits the historical environmental performances of the BC single-family buildings. The mean of the generated distribution is approximately a centrally symmetric distribution (PL_{mean} = 48.6). Furthermore, the smaller standard deviation of $\sigma = 4.8$ highlighted the fact that majority of the buildings performed closer to the mean and fewer buildings performed very low or very high.

The proposed evaluation scale was applied on the probability distribution of the environmental performance to determine the PL thresholds for different evaluation categories (Poor, Fair, Good, and Excellent) and establish the corresponding SPS as shown in Figure 6.31b. As stated above, majority of the buildings showed Fair and Good environmental performance. This pointed to the fact that meeting the environmental strategies/measures discussed within different indicators under the environmental SPCs was easy up to the PL values close to mean. However, it was difficult for the building project to address strategies/measures such that their performance level go beyond the mean.

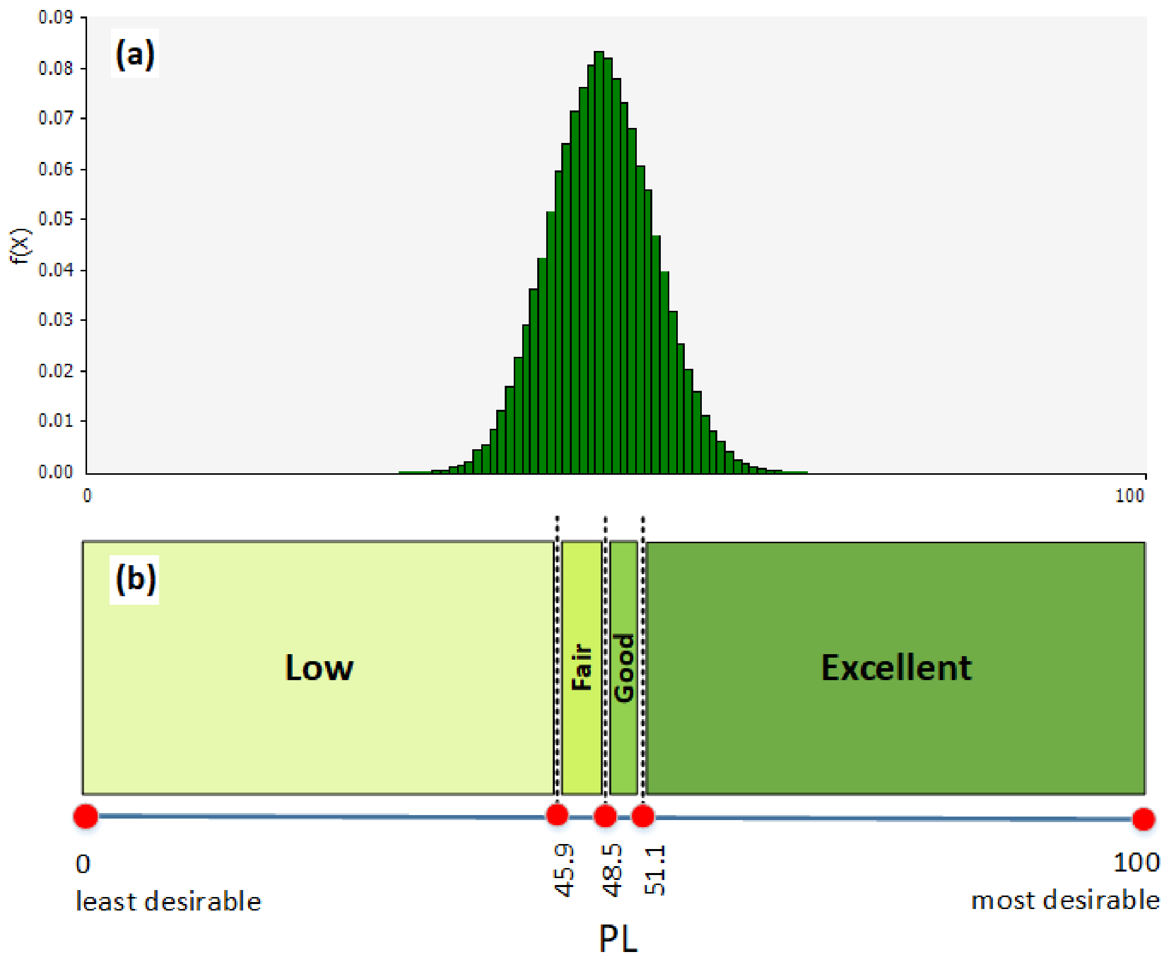

Figure 6.31 (a) Probability distribution of the historical environmental performance of buildings; (b) Corresponding SPS

The probability distribution of the performance of buildings with respect to the economic dimension of sustainability is demonstrated in Figure 6.32a. Similar trend to that of the environmental performance can be seen in the case of the economic performance. However, the mean was slightly higher than the mean of the environmental performance which indicated a marginally better average performance. Nevertheless, the higher standard deviation of 6.7 pointed out that although the PL_{mean} for the economic performance is bigger than that of the environmental performance, there are more variations in the PL of different buildings with respect to the economic performance. This is the main reason why in the established SPS, the PL intervals associated with the Fair and Good performance categories are wider compared to the corresponding PL intervals in the environmental SPS (Figure 6.32b).

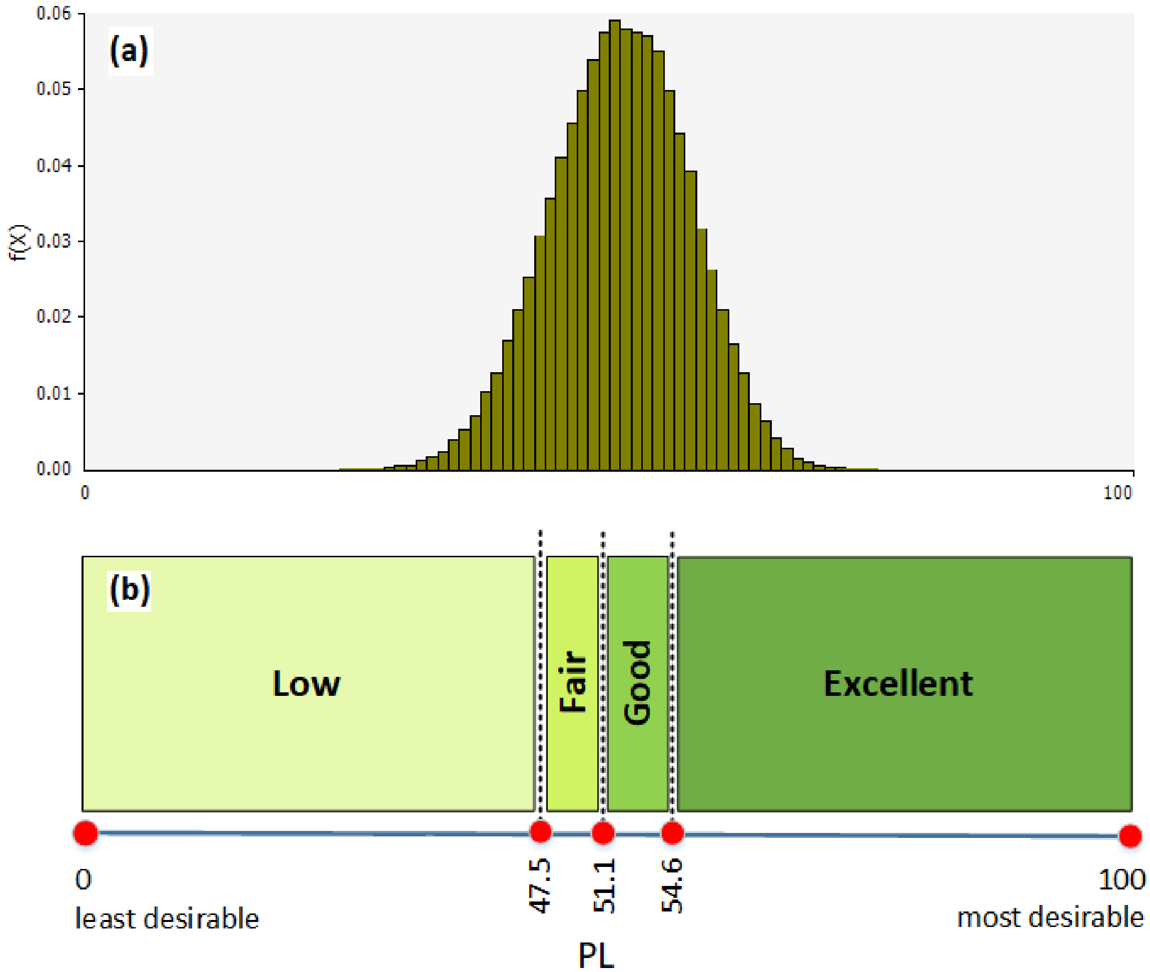

Figure 6.32 (a) Probability distribution of the historical economic performance of buildings; (b) Corresponding SPS

In general, the PL threshold to present a moderate performance was not a small value in both the environmental and economic (59.9 and 47.5, respectively). However, this does not mean that reaching such PL values in a building is difficult since the historical performances of existing buildings showed. It is also worth to state that due to narrow intervals of the Fair and Good evaluation categories, slightly improvement of the underperforming SPIs and sub-SPIs in the designs and construction of new building can enhance the overall environmental and economic performance levels to Excellent level. However, this might not be easy to implement and also can be cost effective as highlighted by the generated probability distributions.

6.6 Sustainability Performance Scale for Overall Sustainability

The overall life cycle sustainability performance of single-family buildings can be explored using the corresponding environmental and economic performances. In this regard, using the same MCS method, the probability distributions of the environmental and economic dimensions combined to explore the overall sustainability performance of single-family buildings in BC. Figure 6.33a illustrates the results of the simulation analyses for the overall sustainability. This centrally symmetric distribution (PL_{mean} = 49.9) highlighted the fact that, on average, half of the available PLs for overall sustainability has been met by the buildings. In addition, the standard deviation of $\sigma = 4.1$ shows that the PL of the majority of buildings have been around the mean.

Figure 6.33b presents the established SPS for benchmarking the overall sustainability (Level 1). Because the probability distribution is centrally symmetric, the mean PL value and the PL threshold between the Fair and the Good performance categories were coincident. To benchmark the overall sustainability performance of a building, the overall sustainability index (*OVERALLi*) should be calculated (see Chapter 5) and compared to the performance categories in the proposed SPS. Consequently, to improve the sustainability performance, the contributing factors, such as underperforming SPCs, should be improved identified and improved.

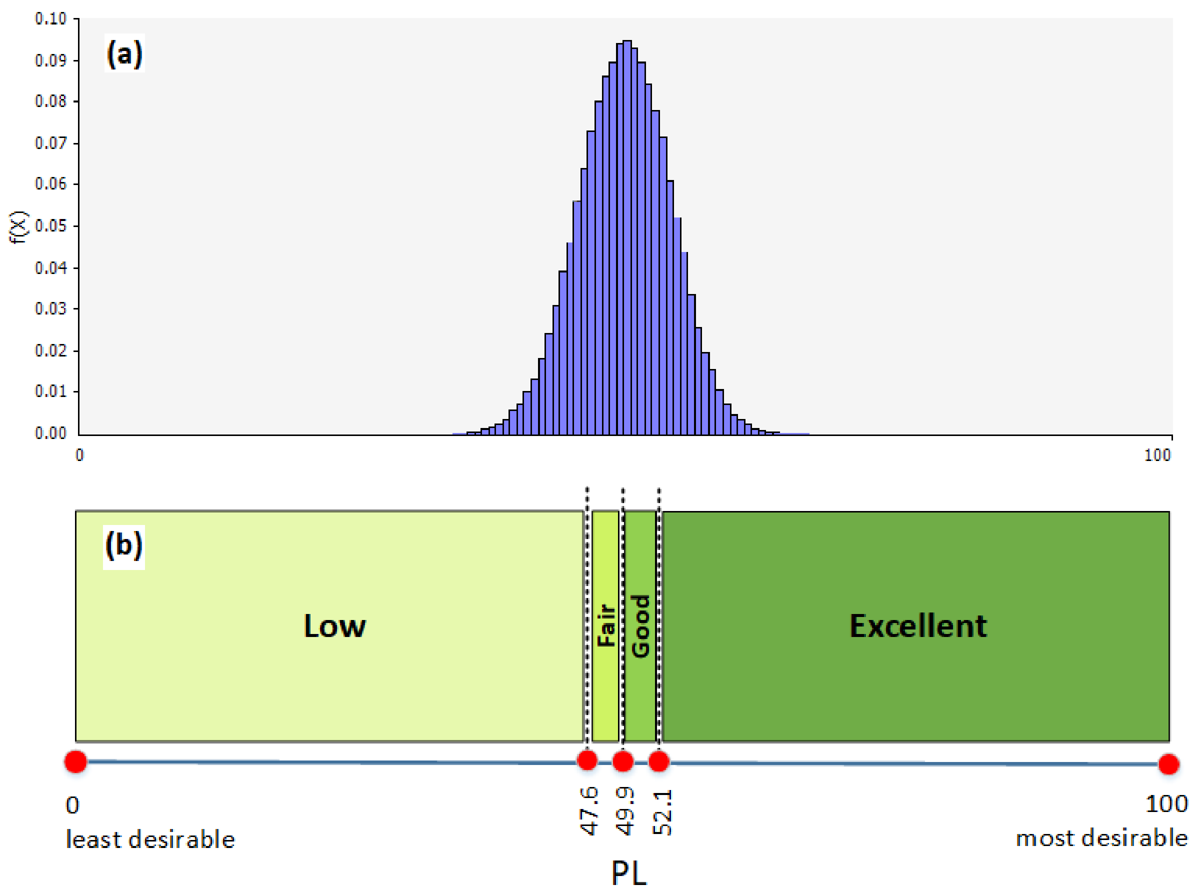

Figure 6.33 (a) Probability distribution of the overall sustainability performance of buildings; (b) Corresponding SPS

6.7 Proposed Decision Support Framework

The primary objective of this research is to develop a decision-support framework for sustainability performance assessment of residential modular buildings based on the life cycle thinking approach. In this research, this was accomplished by incorporating the developed frameworks, methodologies, and deliverables, resulted from all the previous phases of the research into a single comprehensive sustainability assessment framework. The resulted framework is in the form of a multi-level decision support framework (DSF) as presented in Figure 6.34.

The proposed DSF comprises a bottom-up quantification approach and a top-bottom assessment approach. The quantification process starts at calculation of the most independent indicators (i.e., sub-SPIs) and continues up to calculation of the most dependent level, i.e., the overall sustainability index, for the subject building. On the contrary, the assessment process starts at the highest level, i.e., the overall sustainability, and continues down to benchmark the performance of the subject building at lower levels.

It should be stressed that it is not necessary to follow all the components of the proposed DSF and evaluate the sustainability performance of the subject building at all levels. Nevertheless, the user or decision maker (DM) might decide to choose a specific level and focus on that. Therefore, it is only required to follow and implement the corresponding components. For example, the DM wants to benchmark only the energy performance of the subject building. Consequently, only the data required for quantification of the indicators under the EP SPC should be collected to develop the sustainability index for this SPC (i.e., *EPi*) and evaluate it using the corresponding sustainability performance scale (SPS).

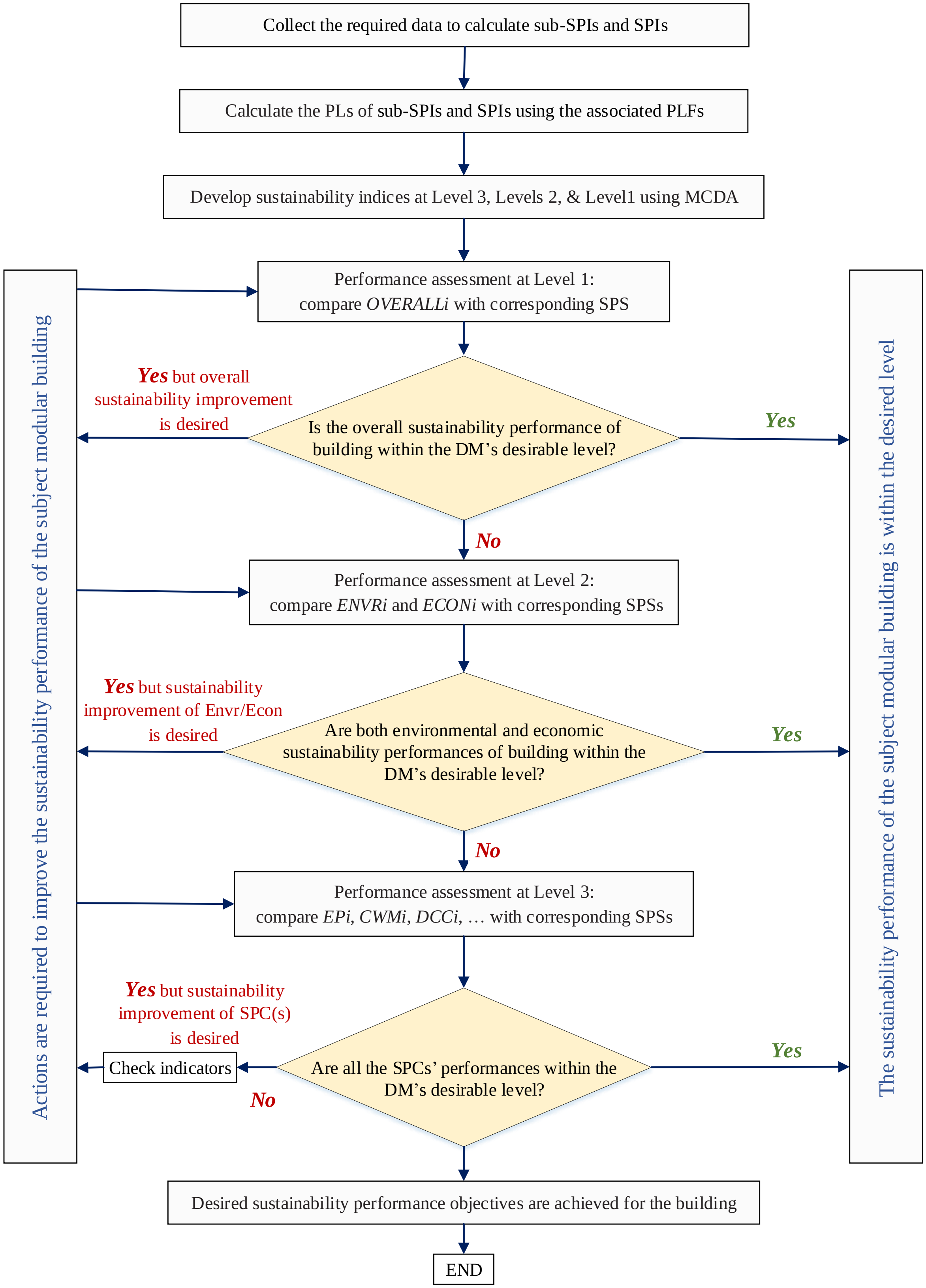

Figure 6.34 Proposed DSF for life cycle sustainability assessment of residential modular buildings

6.7.1 Quantification Process

The quantification process commences by collecting the data of the subject modular building project that is required to calculate all the indicators (i.e., SPIs and sub-SPIs) associated with the selected environmental and economic SPCs. Each sub-SPI and SPI is then calculated and presented in a performance level (PL) between 0 and 100 using the established performance level function (PLF).

As soon as the indicators are calculated, the next step is to combine the PLs of the indicators and their relative importance weights using a suitable aggregation process (TOPSIS MCDA method) which results in development of a sustainability index for each SPC (Level 3), i.e., *EPi*, *CWMi*, *DCCi*, and so forth. The same aggregation process is used to combine the sustainability indices of the SPCs and their weights to develop sustainability indices for environmental and economic sustainability dimensions (Level 2), i.e., *ENVRi* and *ECONi*. Similarly, the overall sustainability index, i.e., *OVERALLi*, is developed by combining *ENVRi* and *ECONi* and the weights of the environmental and economic dimensions (Level 1).

6.7.2 Assessment Process

In the assessment process, the performance of the subject building is benchmarked. The process commences at the overall sustainability level (Level 1) by comparing the corresponding sustainability index (i.e., *OVERALLi*) with the established SPS for this level. If the performance falls within the performance category that the DM desires, the assessment process is completed. However, if the performance is lower than the desired level, or if it is desirable but the DM still wishes to investigate the contributing criteria to further improve the overall sustainability performance of the building, the assessment process continues by moving to the next level (Level 2). At this level, the performance of the subject building with respect to the environmental and economic sustainability dimensions is benchmarked by comparing the developed sustainability indices (i.e., *ENVRi* and *ECONi*) with the corresponding SPSs. Consequently, the underperforming sustainability dimensions that caused the overall sustainability performance of the building to be lower than the DM’s desired level are investigated. This can be due to low performance of the building with respect to both or one of the sustainability dimensions. Even if the latter occurs, the DM might also want to improve the performance of the building with respect to both sustainability dimensions. Therefore, the assessment process shifts to Level 3 where the low performing SPCs are identified by comparing the sustainability indices with the corresponding SPSs. To improve each underperforming SPC, the associated SPIs and sub-SPIs are investigated. Finally, appropriate decisions are made to improve the low performing indicators.

It should be mentioned that, the quantification and assessment processes of the proposed DSF have been explained above by assuming that a modular building design is under study to identify its performance levels at different levels and to recognize the underperforming areas that need improvements. However, if no changes can be made in the design and construction of the building, the described processes can be still useful. This is because identification of the low and high performing areas of the subject modular building can assist with improvement of the sustainability of similar modular projects in the future by considering suitable design and construction features. In addition, identification of the high performing areas can help the DM to avoid unnecessary investments on such areas, and instead, to allocate costs to improve the performances of underperforming areas. Furthermore, the proposed DSF can also be used for comparisons of two or more buildings that are to be constructed by either modular or conventional methods. The results can assists with selection of the most sustainable construction options.

In general, it is recommended that decision makers, first, define their preferences and limitations, such as sustainability performance desired levels, priority sustainability dimension, cost constraints, time constraints, technological constraints, and so forth, before starting the assessment process. By defining the preferences and limitations in advance, the results of the sustainability performance benchmarking by the proposed DSF can assist with informed decision options.

6.8 Summary

In order to performance benchmarking a modular building, the developed sustainability indices at different levels (Chapter 5) should be compared to the corresponding benchmarks. Therefore, in the first part of this chapter, suitable sustainability performance scales (SPSs) were established at the corresponding levels. In this regards, three surveys were conducted to capture experts' opinions on the performances of the single-family buildings with respect to the independent indicators under each SPC. Subsequently, using the collected data, suitable probability distributions were constructed for these indicators. Then, these distributions were used as the inputs of the MCS to generate the probability distributions of the SPCs. Similar analyses were performed to generate the distributions of the sustainability dimensions and the overall sustainability. Subsequently, a suitable evaluation scale was chosen based on the literature review and applied to each of the produced distributions. Finally, the SPSs were established at different levels (SPCs, sustainability dimensions, and overall sustainability) each of which included four evaluation categories: Poor, Fair, Good, and Excellent. The developed sustainability indices can be benchmarked at each of the three levels using the corresponding

SPSs.

In the second part of Chapter 6, all the frameworks, methodologies, and deliverables of the research were incorporated into a single framework as a comprehensive decision support framework (DSF) for sustainability assessment of residential modular buildings. The proposed DSF can assist with exploration and improvement of the low sustainability performing areas over the life cycle of a new modular building design. It can also assists with making informed decisions on selection of the best method of construction (modular vs. conventional).

Chapter 7 Validation of the Integrated Sustainability Assessment Framework

A part of this chapter is under review in:

- *Energy and Buildings* entitled "Comparing environmental impacts of different construction methods: Cradle-to-gate LCA for residential buildings in BC, Canada" (Kamali et al. 2019e).

In this chapter, the proposed multi-level decision support framework (DSF) are validated using case study of modular buildings in British Columbia, Canada.

7.1 Background

In Chapter 6, all the deliverables of this research were merged into an integrated sustainability assessment framework as a multi-level decision support framework (DSF). In the present chapter, application of the proposed DSF was illustrated with two case study modular buildings designed and constructed in the Okanagan, BC, Canada.

As mentioned previously, the proposed DSF can be used in different ways. In other words, depending on the scope and aim of a study, the user or decision maker (DM) can select to assess the performance of the subject building at all levels or even only a particular SPC. The scope of the case study analysis in this chapter is to benchmark the case study modular building projects at all levels.

In the first part of this chapter, all the components of the proposed DSF were carefully implemented to develop the sustainability indices for two case study modular buildings. The developed indices were then used to evaluate the environmental and economic performances of the case study buildings.

In the second part of this chapter, the performances of the case study modular buildings with respect to the GE SPC were evaluated. It is necessary to remind that, the method of index development and performance evaluation in the case of the GE SPC was different from the other SPCs and was based on LCA studies. Therefore, the associated analyses and assessment process for this SPC was provided separately.

The detailed descriptions of the case study buildings, data collection, criteria quantification, and sustainability assessment are presented in the following sections.

7.2 Performance Evaluation of the Case Study Buildings at Different Levels

7.2.1 Description of Case Study Modular Buildings

Four modular homebuilders in the Okanagan that build single-family homes were contacted by emails and phone calls and invited to participate in the research. In addition, they were met in person at their offices to discuss about the requested data of their building projects. Three homebuilders showed interest and a number of additional meeting were held with each of them to discuss the details of the questions and clarify ambiguities. However, after a number of meetings, two of these homebuilders did not participate due to their tight schedule and limited human resources. Eventually, two homebuilders (henceforth Mod1-builder and Mod2-builder) provided the requested data for two of their modular building projects (henceforth Mod1 and Mod2). Both Mod1-builder and Mod2-builder are known modular homebuilders in Canada that design and construct diverse modular buildings with the total annual floor areas of 408,000 ft^2 and 300,000 ft^2, respectively. The completed modules of their buildings are transported to different locations throughout BC and placed on permanent foundations to form the final products. However, in the process of research participation invitation, the participating homebuilders were requested to provide the data for one of their common single-family houses for which the final site is within the Okanagan.

The floor plans of the case study modular buildings are presented in Figure 7.1. As highlighted by dashed lines, Mod1 and Mod2 comprise three and two modules, respectively. With the total floor area of 1480 ft^2 (138 m^2), Mod1 consists of three bedrooms, two bathrooms, one living room, one dining room, one kitchen, and one den. The Mod2 building is a bigger house with the total floor area of 1782 ft^2 (165 m^2) that includes three bedrooms, two bathrooms, one living room, one family room, one dining room, one kitchen, one WIC, and one den.

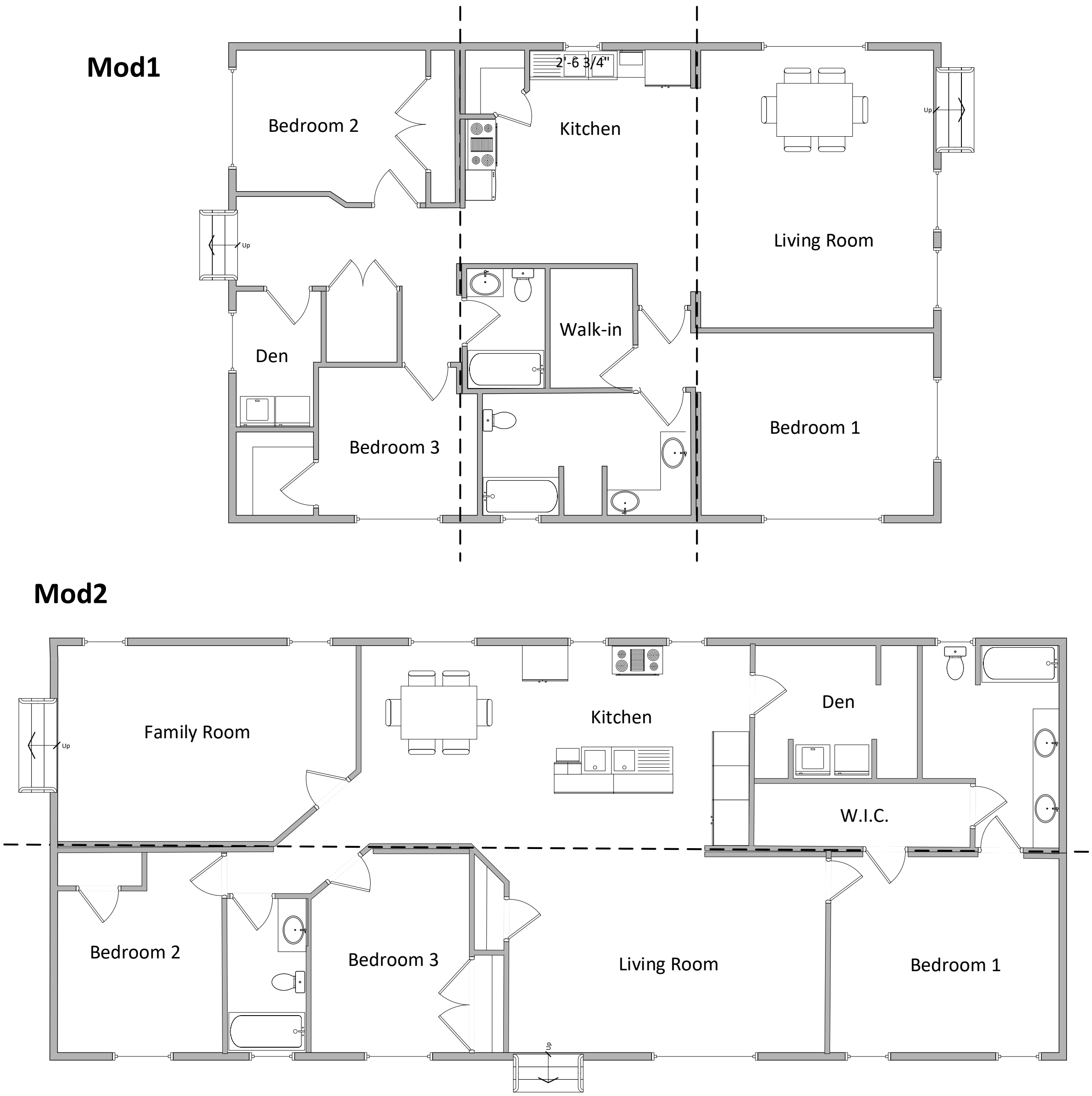

Figure 7.1 Floor plans of the case study modular buildings (Mod1 and Mod2)

7.2.2 Data Collection for Development of Sustainability Indices

To quantify different indicators and develop the corresponding SPCs, the data of the case study buildings should be available. To facilitate the process of data collection, a questionnaire survey (Survey E) was designed by including all the questions related to the required data. Survey E consisted of two main sections. After description of the survey (e.g., research objective and benefits, confidentiality, duration, consent statement, and so forth), in the first section, general questions about the case study building such as location, size, frame type, floor plan, were included. Then, in the second section, the questions related to the required data for analyses were asked. It should be stated that, the name of the indicators associated with the questions and also their calculation methods were not disclosed. As seen in Chapter 5, several indicators (sub-SPIs and SPIs) have been determined under the environmental and economic questions. Consequently, several questions were needed to be included in the questionnaire to collect the required data for quantification of the indicators. This is why the page count of Survey E came to be over 30 pages. However, it had been designed in a way that the format and type of questions were straightforward and easy to follow. Thus, the participating homebuilders did not complain about the length of the questionnaire.

As mentioned above, Mod1-builder and Mod2-builder participated in Survey E by providing the data of one common modular building project they produce. After the initial meetings, the questionnaire was sent to them. Then, during a number of follow up and clarification meetings at their offices (i.e., modular manufacturing centers) in Kelowna and Penticton, BC, the answers to all questions were collected. It should be mentioned that, since some of the questions were related to the site activities such as site preparation and foundation, the answers to such questions were asked by the participating homebuilders from their contractors who perform these activities.

7.2.3 Sustainability Indices

In this section, the aggregated sustainability indices for SPCs (Level 3), sustainability dimensions (Level 2), and overall sustainability (Level 1) have been developed separately for each case study building. First, the performance levels (PLs) of all the sub-SPIs were calculated by putting the collected data in their established performance level functions (PLFs). Then, these PLs were put into the PLFs of the corresponding SPIs to obtain their PLs. Subsequently, the aggregated sustainability indices for SPCs (Level 3) were developed by aggregating the calculated PLs of the SPIs and their weights through step-by-step implementation of the TOPSIS MCDA method. Detailed descriptions of the steps and equations of TOPSIS can be found in Appendix C. Similar process were followed to develop the sustainability indices at Level 2 (i.e., sustainability dimensions) and Level 1 (overall sustainability).

Due to space limitations, only the details of the sustainability index calculation steps for the ‘Energy performance and efficiency strategies (EP)’ SPC of Mod1 are presented. However, results for all the sustainability indices have been included for both case study buildings.

Step 1: Determine the weights of SPIs. The relative importance weights of the SPIs under the EP SPC that have already been determined in Chapter 5 are presented in Table 7.1.

Step 2: Check for normalization need. In this research, the PLs of all indicators are calculated and presented as the benefit criteria ranging from 0 to 100 using their established PLFs. Hence, there is no need for normalization. The results of PL calculations for SPI under the EP SPC are shown in Table 7.1.

Step 3: Calculate the weighted values of indicators (v_{ij}). The weighted PL of each SPI was calculated by multiplying the performance level of the SPI and its corresponding weight (Table 7.1).

Table 7.1 Performance levels, weighted values, PISs, and NISs for the SPIs of the EP SPC

SPI (weight)	EP1 (0.072)	EP2 (0.107)	EP3 (0.107)	EP4 (0.143)	EP5 (0.107)	EP6 (0.214)	EP7 (0.107)	EP8 (0.107)	EP9 (0.036)
PL	48.9	30.0	0.0	50.0	66.7	22.3	0	66.7	100
vij	3.52	3.21	0.00	7.15	7.14	4.77	0.00	7.14	3.60
PIS	7.20	10.70	10.70	14.30	10.70	21.40	10.70	10.70	3.60
NIS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Step 4: Calculate the PIS and NIS values for indicators. The positive-ideal and negative-ideal solutions for the SPIs were calculated in terms of weighted PLs by substituting the most and least desirable performance values (100 and 0, respectively) as presented in Table 7.1. For instance, the PIS and NIS for the EP3 SPI were obtained as:

$$PIS_{EP3} = 100 \times 0.107 = 10.7$$

$$NIS_{EP3} = 0 \times 0.107 = 0.0$$

Step 5. Calculate the separation measures. In this step, the distance of the Mod1's performance with regard to each SPC, from the positive and negative solutions was calculated using the n-dimensional Euclidean distance. For example, the separation measures for the EP SPC was measures as:

$$S^{+}_{EP} = \sqrt{}[(3.52 - 7.20)^2 + (3.21 - \ 0.70)^2 + \ldots + (0.36 - 3.60)^2] = 25.52$$

$$S^{-}_{EP} = \sqrt{}[(3.52 - 0.00)^2 + (3.21 - 0.00)^2 + \ldots + (0.36 - 0.00)^2] = 14.54$$

The results of separation measures for all the environmental and economic SPCs of Mod1 are reported in Table 7.2.

Step 6: Develop the aggregated sustainability indices. As the last step, the aggregated sustainability indices for the selected SPCs are developed by calculating similarities to PIS. For example, the sustainability index for the EP SPC of Mod1 is obtained as:

$$EPi = [S^{-}_{EP}/(S^{-}_{EP} + S^{+}_{EP})] \times 100 = [14.54/(144.54 + 25.52)] \times 100 = 36.3$$

Since the outcome of the above equation is a ratio, it was multiplied by 100 in order to transform it to an index between 0 and 100. Similar to the provided example calculation, the sustainability indices for other environmental and economic SPCs were developed as presented in Table 7.2.

Table 7.2 Separation measures and sustainability indices at different levels for Mod1

		Criteria	S^+	S^-	Sustainability Index
Level 3	Environmental SPCs	Energy performance and efficiency strategies (EP)	25.53	14.54	*EPi* = 36.3
		Regional (local) materials (RM)	4.68	34.26	*RMi* = 88.0
		Construction waste management (CWM)	13.96	58.98	*CWMi* = 80.9
		Renewable and environmentally preferable products (REP)	31.78	11.63	*REPi* = 26.8
		Site disruption and appropriate strategies (SD)	29.02	36.48	*SDi* = 55.7
		Renewable energy use (RE)	69.31	6.66	*REi* = 8.8
	Economic SPCs	Integrated management (IM)	34.48	39.45	*IMi* = 53.4
		Durability of building (DB)	8.32	53.07	*DBi* = 86.4
		Adaptability of building (AB)	34.29	25.28	*ABi* = 42.4
		Design and construction time (DCT)	4.50	83.10	*DCTi* = 94.9
		Design and construction costs (DCC)	1.32	93.02	*DCCi* = 98.6
		Operational costs (OC)	42.30	57.70	*OCi* = 57.7
		Maintenance costs (MC)	52.10	47.90	*MCi* = 47.9
		Investment and related risks (IRR)	0.70	99.30	*IRRi* = 99.3
Level 2		Environmental dimension	22.60	24.36	*ENVRi* = 51.9
		Economic dimension	11.37	28.92	*ECONi* = 71.8
Level 1		Overall sustainability	27.14	45.15	*OVERALLi* = 62.5

Using the developed sustainability indices at Level 3, the same aggregation process was performed and the sustainability indices for each of the sustainability dimensions and the overall sustainability were developed and presented in Table 7.2. As discussed before, the inputs of the aggregation process to develop the sustainability indices at Level 3 were the PLs of the SPIs and their weights. However, in developing the sustainability index for each sustainability dimension, the inputs were the developed sustainability indices of the associated SPCs along with the corresponding weighs. Likewise, in developing the sustainability index for the overall sustainability, the inputs were the developed sustainability indices of the environmental and economic dimensions and the relative importance weighs of these dimensions. All the required weight sets have been previously determined in Chapter 5.

Identical aggregation process explained above has been implemented using the collected data of the Mod2 building to develop the corresponding sustainability indices. The results are provided in Table 7.3.

Table 7.3 Separation measures and sustainability indices at different levels for Mod2

		Criteria	S^+	S^-	Sustainability Index
Level 3	Environmental SPCs	Energy performance and efficiency strategies (EP)	22.24	18.93	*EPi* = 46.0
		Regional (local) materials (RM)	8.72	31.62	*RMi* = 78.4
		Construction waste management (CWM)	12.49	67.32	*CWMi* = 84.4
		Renewable and environmentally preferable products (REP)	36.73	0.00	*REPi* = 0.0
		Site disruption and appropriate strategies (SD)	35.64	30.17	*SDi* = 45.8
		Renewable energy use (RE)	68.34	13.34	*REi* = 16.3
	Economic SPCs	Integrated management (IM)	27.50	40.61	*IMi* = 59.6
		Durability of building (DB)	8.32	53.07	*DBi* = 86.4
		Adaptability of building (AB)	32.04	28.68	*ABi* = 47.2
		Design and construction time (DCT)	10.12	82.38	*DCTi* = 89.1
		Design and construction costs (DCC)	2.70	93.00	*DCCi* = 97.2
		Operational costs (OC)	84.50	15.50	*OCi* = 15.5
		Maintenance costs (MC)	73.40	26.60	*MCi* = 26.6
		Investment and related risks (IRR)	23.50	76.50	*IRRi* = 76.5
Level 2		Environmental dimension	23.88	24.22	*ENVRi* = 50.4
		Economic dimension	15.80	24.36	*ECONi* = 60.7
Level 1		Overall sustainability	31.30	39.90	*OVERALLi* = 56.0

7.2.4 Performance Evaluation at Different Levels

After the sustainability indices were developed, the life cycle performance of each case study modular building can be benchmarked. According to the proposed DSF in this research, the assessment process is performed by comparing the developed sustainability indices at each level with the corresponding sustainability performance scales (SPSs). As discussed in Chapter 6, the SPSs were established based on the historical performances of single-family conventional buildings in BC with the focus on the Okanagan.

Figure 7.2 compares the overall sustainability performance of the case study buildings with the industry's benchmarks. It can be observed from this figure that although both buildings showed Excellent sustainability performance, Mod1 showed a better performance compared to Mod2 whose performance is slightly better than Good.

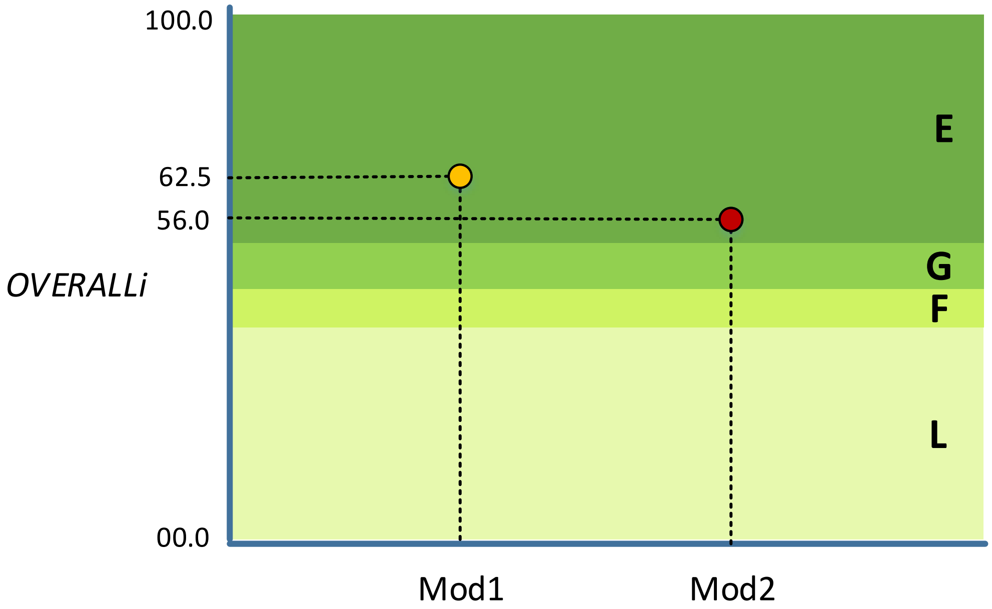

Figure 7.2 Sustainability performance benchmarking of the case study buildings (Level 1)

As discussed before, Excellent overall performance of a building does not necessarily indicate that the same Excellent performance occurs in lower levels (Levels 2 and 3). Therefore, to understand the performance of the case study buildings with respect to each of the sustainability dimensions, the assessment process moved to Level 2. The DM might wish to find out which sustainability dimension needs urgent attention to fall into the desired performance category. Furthermore, even both sustainability dimensions are within the DM's desirable levels, he/she might want to improve the performance of one or both dimensions in order to further improve the overall sustainability. In other words, it might be a situation that the performance of the subject building with respect to both environmental and economic sustainability is acceptable; however, by implementation of a number of strategies at lower costs, the performance at Level 2 can be improved which can result in the improvement of the overall sustainability.

The environmental and economic performances of the buildings have been compared with the corresponding SPSs in Figure 7.3. It can be observed from the figure that not only the overall sustainability performance of Mod1 is better than Mod2, but also both individual sustainability dimensions. Nevertheless, although both *ENVRi* and *ECONi* of Mod1 were located in the Excellent performance category, the *ECONi* is close to the lower threshold of this category. On the other hand, the *ENVRi* of Mod2 is slightly less than *ENVRi* of Mod1 very close to the upper threshold of the Good performance category.

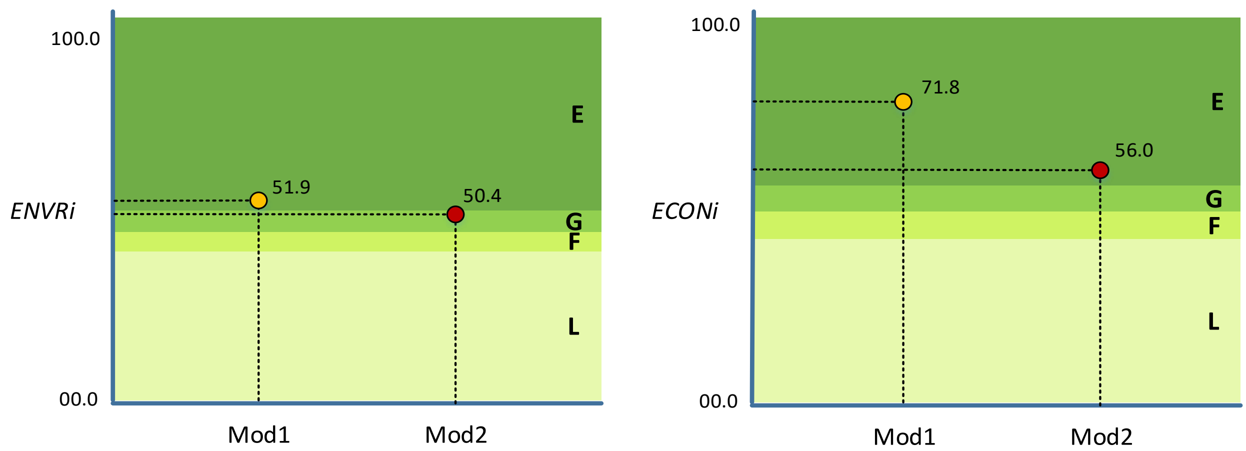

Figure 7.3 Environmental and economic performance benchmarking of the case study buildings (Level 2)

In the next step, the assessment process was continued at Level 3 where the sustainability performances of Mod1 and Mod2 with respect to each SPC were evaluated. Figures 7.4 and 7.5 demonstrate the performance of the case study buildings with respect to the environmental SPCs and economic SPCs, respectively.

It can be observed from Figure 7.4 that ‘Regional materials (RM)’ and ‘Construction waste management (CWM)’ are the two areas that the Mod1 building has shown Excellent performance. In addition, this building performed close to Excellent in terms of ‘Site disruption and appropriate strategies (SD)’. However, in the other three SPCs, the building have shown a Poor performance. Similarly, the Mod2 building also showed an Excellent performance for the RM and CWM SPCs. However, in the remaining areas, its performance has not been satisfactory.

When the performances of the two buildings are compared with each other (i.e., review benchmarking), as opposed to what was observed previously at Level 2, the Mod2 building performed higher than Mod1 in terms of some environmental SPCs. For example, although both buildings have implemented suitable construction waste management strategies, Mod2 obtained a higher *CWMi*. Similarly, even though both Mod1 and Mod2 have fallen into the Low performance category in the cases of the EP and RE SPCs, the corresponding sustainability indices for the latter building are higher.

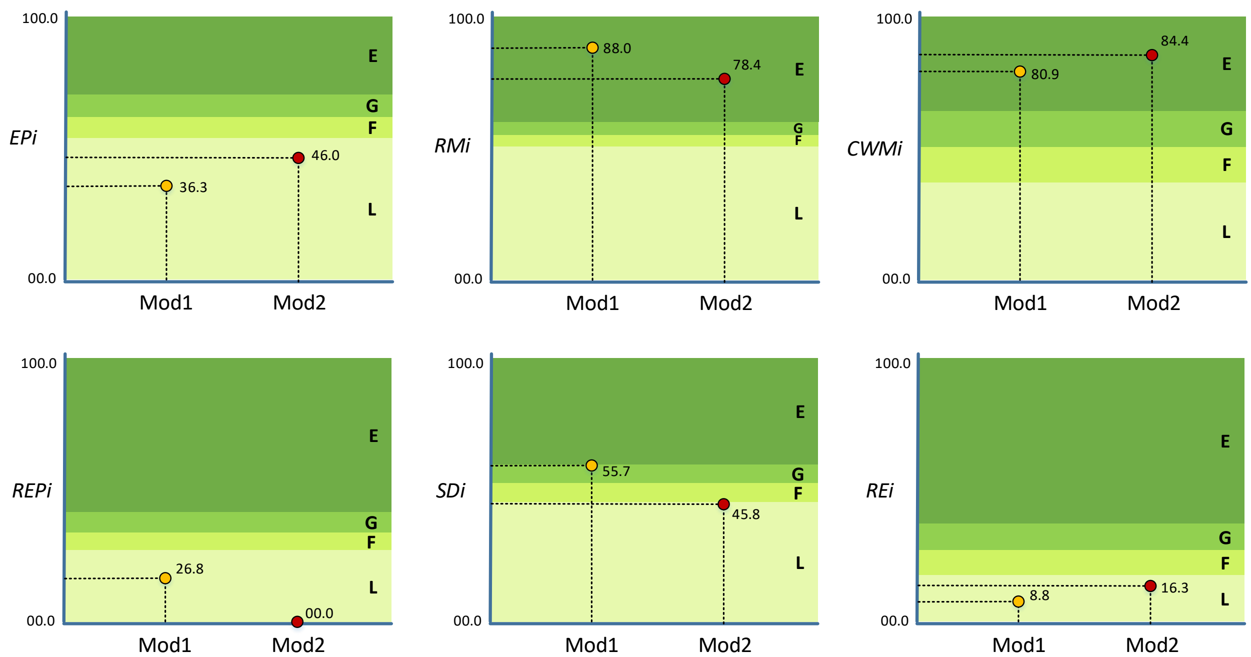

Figure 7.4 Sustainability performance benchmarking of the case study buildings with respect to environmental SPCs (Level 3)

Comparisons of the performances of the case study buildings with respect to the economic SPCs have been presented in Figure 7.5. It can be observed from this figure that, in general, the sustainability indices for both Mod1 and Mod2 have fallen in high performance categories such as Excellent and Good. Except the 'Maintenance costs (MC)' and to some extent the 'Operational costs (OC)', both modular buildings performed remarkably. In the cases of five SPCs including IM, DB, DCT, DCC, and IRR, the corresponding sustainability indices were very high indicating outstanding economic performances. Among these five SPCs, an excellent performance for the 'Design and construction time (DCT)' was anticipated because fast construction is among the most cited benefits of modular construction in the literature. Supporting this, the DCT SPC was ranked 1st among the economic SPC category and 2nd among the TBL SPCs by the construction practitioners previously in this research (see the results of Chapter 4). When comparing the performances of Mod1 and Mod2 with each other, each building showed a better performance with respect to a number of economic SPCs.

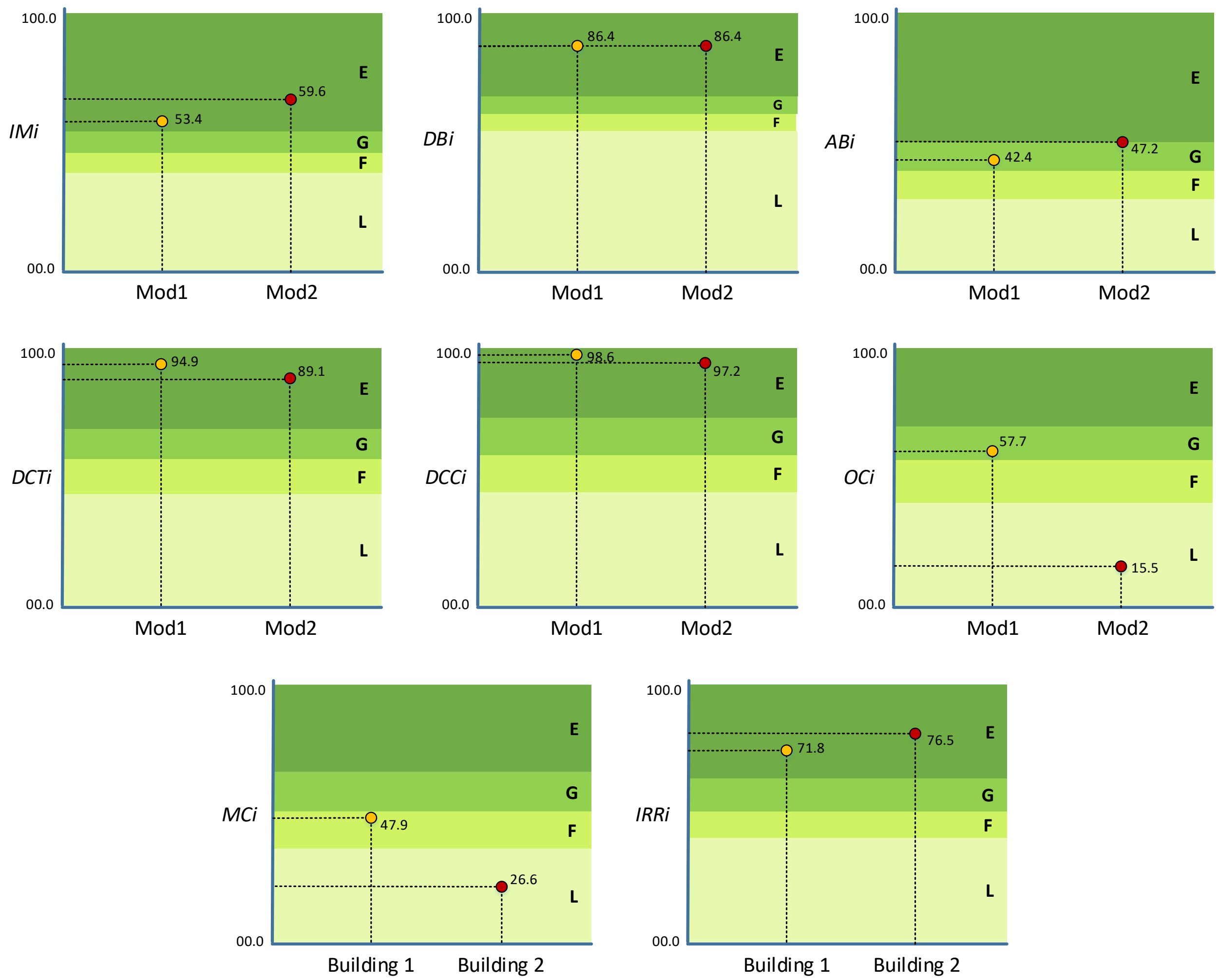

Figure 7.5 Sustainability performance benchmarking of the case study buildings with respect to economic SPCs (Level 3)

7.2.4.1 Sensitivity analysis

The DM can take guidance from the results of the above sustainability performance evaluations and understand which SPCs should be prioritized for improvement actions. However, to identify what SPIs and sub-SPIs contribute more to each of the underperforming SPCs, a sensitivity analysis is required. Typically, the most natural sensitivity analysis is to check which uncertain inputs (i.e., sub-SPIs, SPIs) have the largest effects on a given output (i.e., SPCs). Sensitivity analysis on results of different analyses are performed to see which of the uncertain inputs have the largest effects on the outputs.

By assuming that the DM's desired performance target for both Mod1 and Mod2 with respect to all SPCs has been set at Good, the sensitivity analysis was conducted. To this end, the @Risk software was used to perform the sensitivity analysis on all the SPCs whose sustainability indices fell into either the Poor or Fair performance categories.

From Figure 7.4, it can be observed that, both buildings showed a Poor environmental performance in terms of EP, REP, and RE SPCs. In addition, Mod2 also performed unsatisfactory with respect to the SD SPC. Figure 7.6 presents the results of the sensitivity analysis for the EP, REP, and SD SPCs in the form of tornado charts. In a tornado chart, the longest bars are at the top of the chart. In addition, the longer the bar, the more effect the corresponding uncertain input has on the output. It should be mentioned that the sensitivity analysis can be performed for each of the Good and Excellent performing SPCs if the DM wants to investigate the top priority indicators for further improvement of thse SPCs.

The indicators correspond to top bars in Figure 7.6a including the EP5 and EP7 SPIs and also the EP6-3 and EP6-1 sub-SPIs should be given high priority to improve the performance of the ‘Energy performance and efficiency strategies’ SPC. Similarly, from Figure 7.6b, it can be seen that the REP2-2 sub-SPI and REP3 SPI are among the top concerns to improve the performance of the ‘Renewable and environmentally preferable products’ SPC. The remaining indicators have not a significant difference in their contributions to this SPC. In the same way, Figure 7.6c can be used to rank the indicators under the ‘Site disruption and appropriate strategies’ for sustainability performance improvement actions.

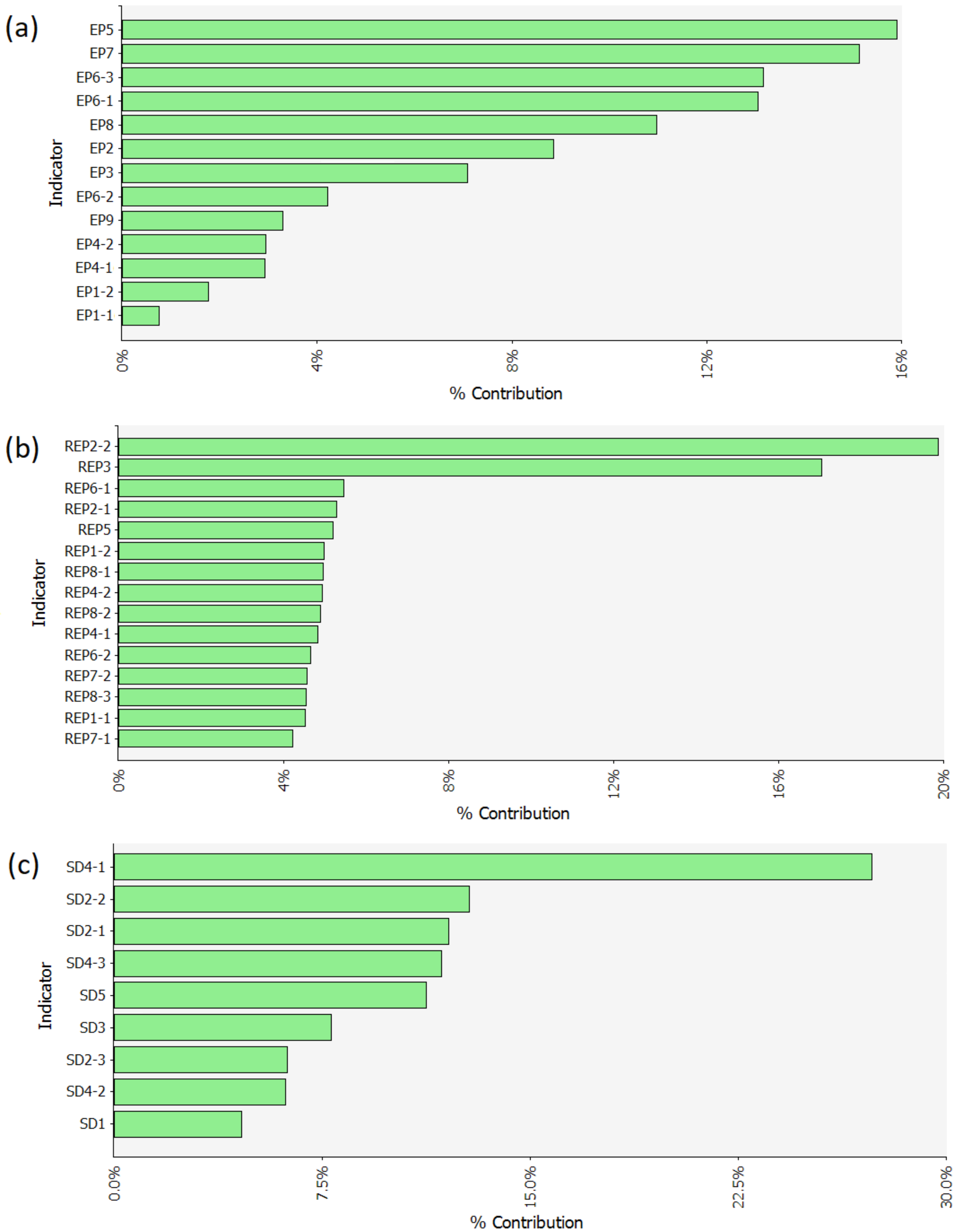

Figure 7.6 Sensitivity analysis results (a) Energy performance and efficiency strategies; (b) Renewable and environmentally preferable products; (c) Site disruption and appropriate strategies

In the cases of the economic SPCs, as shown in Figure 7.5, the MC performance of Mod1 and Mod2 have performed Fair and Poor, respectively. Furthermore, Mod2 did not show a satisfactory performance with respect to OC (i.e., Poor performance). Since both the OC and MC SPCs consisted of only one SPI, the results of the sensitivity analysis showed 100% contribution of each SPI to the corresponding output SPC. Therefore, to improve the MC performance, both Mod1-builder and Mod2-builder should investigate the reasons for high maintenance costs and make appropriate remedy decisions to apply in new buildings. For example, it could be due to inappropriate installation of different equipment in the building that resulted in the need for service and repairs. Similarly, Mod2-builder needs to find out the reasons for the higher running costs in the use phase. This could be because of the quality of insulations, low performance of some appliances, and so forth.

7.3 Performance Evaluation of the Case Study Buildings with respect to the GE SPC

7.3.1 Data Collection for Inventory Analysis

The methodology used in this research to develop the environmental impact indices has already been explained in Chapters 5 and 6 (see sections 5.3.7 and 6.3.7 for details); therefore, detailed explanations are not repeated. As stated earlier, in this study, two modular single-family buildings (i.e., Mod1 and Mod2) along with one conventional single-family building (henceforth Conv) were evaluated in terms of environmental impacts due to construction of these buildings. Figure 7.7 illustrates the floor plan of the Conv building. The total floor area of this building is 1568 ft^2 (146 m^2), which includes three bedrooms, two bathrooms, one living room, one dining room, one kitchen, one WIC, and one den.

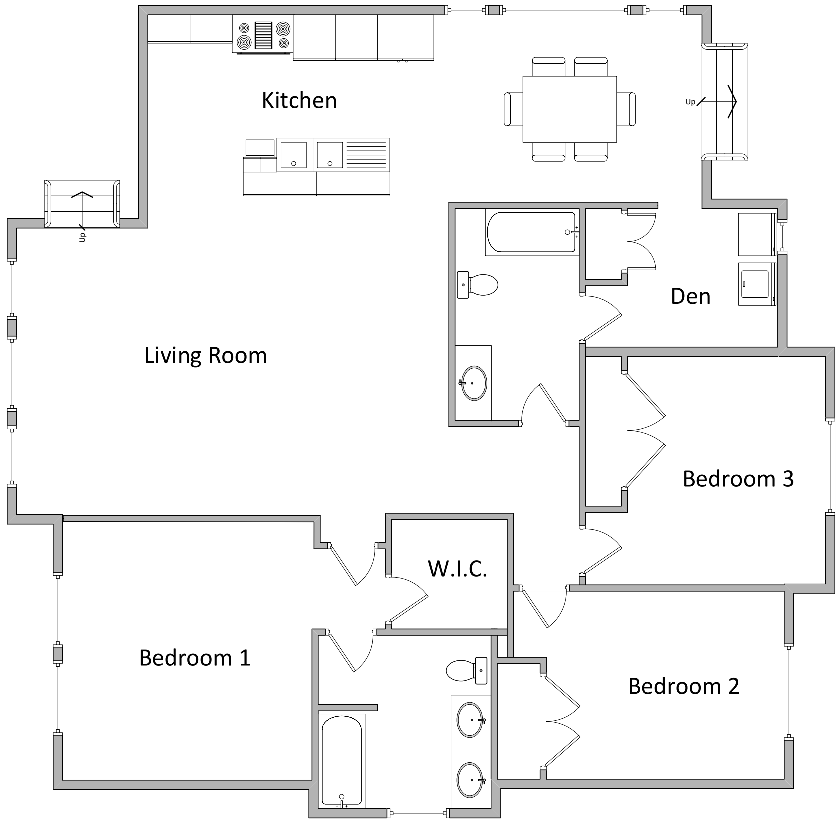

Figure 7.7 Floor plan of the case study conventional building (Conv)

Based on informal communications with conventional construction experts, for specifications such as material quantity, cost, construction duration, and quality, there is a more direct relationship with square footage, even though not strictly linear, among single-family buildings under 3000 ft^2. Buildings with the total living floor area above 3000 ft^2 are usually custom-made buildings; therefore, the type and quality of the materials, project duration, and the subsequent on-site energy, among others, can be nonlinearly different. Therefore, the functional unit of 1 ft^2 is suitable for comparisons of single-family buildings under 3000 ft^2. The conventional case study building was constructed by one of the known construction firms in the Okanagan, henceforth Conv-builder. According to Conv-builder, this building is one of the typical single-family building projects that have been constructed for many clients. Regardless of different floor plans, similar wood-frame building projects in the Okanagan use similar material types and layers in different assemblies of the buildings. Furthermore, the supply chain for the materials and products as well as the modes of material and worker transportation can be assumed the same for similar projects. Therefore, Conv can adequately represent the average-quality wood-frame single-family buildings under 3000 ft^2 in the Okanagan, BC.

As stated before, a questionnaire survey (Survey D) was conducted to collect the required data of the two modular and one conventional case study buildings from the corresponding homebuilders for inventory analysis (LCI) (see Table 5.10 in Chapter 5). In addition, a copy of the design drawings of each building was requested. Subsequently, using the received design drawings, different assemblies, their dimensions, and the materials and products used in each assembly were calculated and entered into the Athena software as the input raw data. The software performed inventory analysis and calculated the energy associated with the material production phase (i.e., A1 and A2) and the construction phase (i.e., A3 and A4) of each building. As discussed before, the software was not able to calculate the energy related to a number of tasks under the activity categories A3 and A4. However, if these energy consumptions are separately calculated, Athena is capable of performing LCIA to calculate the corresponding impact measures. Therefore, for such tasks under the activity categories A3 and A4, the associated energy consumptions were separately modeled and calculated based on the information provided by the homebuilders in the questionnaire forms. For example, the energy consumed in the modular factory for machinery, office, heating, and cooling to construct Mod1 was calculated using the annual energy bills and the total annual module production (ft^2) provided by the Mod1-builder. The calculated energy values were then fed into the software for LCIA.

7.3.2 Impact Assessment

Based on the results of the inventory analysis, the life cycle impact assessment (LCIA) was performed by the Athena Impact Estimator to calculate the environmental impact measures. Table 7.4 presents the results of LCIA for the case study buildings. The environmental impacts due to material and energy consumption in the material production phase (i.e., activity categories A1 and A2) and the construction phase (i.e., activity categories A3 and A4) of the buildings have been provided separately. In addition, the accumulative values of the impact measures for both of these life cycle phases have been included in the table that indicate the cradle-to-gate environmental impacts of each building. The results were normalized to the functional unit (i.e., 1 ft^2 of the total floor area of buildings) that enables valid comparisons between the buildings. Except the eco-toxicity effect, all the impact measures have been generated directly by the impact assessment. The eco-toxicity measure, as explained earlier, was calculated for each building by aggregating the mass of the identified toxic substances and their weights (Equation [5.85]), and then normalized and reported.

Table 7.4 Results of LCIA for the benchmarking buildings

		Material production phase (A1 & A2)			Construction phase (A3 & A4)			Cradle-to-gate (A1 - A4)		
LCA impact measures	unit	Conv	Mod1	Mod2	Conv	Mod1	Mod2	Conv	Mod1	Mod2
Global warming potential	kg CO_2eq	5.14E+00	4.85E+00	4.66E+00	4.65E+00	3.75E+00	5.11E+00	9.79E+00	8.60E+00	9.78E+00
Acidification potential	kg SO_2eq	3.78E-02	3.95E-02	3.77E-02	2.09E-02	1.74E-02	2.88E-02	5.87E-02	5.69E-02	6.65E-02
Human health effect	kg PM2.5eq	8.08E-03	1.09E-02	1.05E-02	1.15E-03	9.40E-04	1.40E-03	9.23E-03	1.19E-02	1.19E-02
Eutrophication potential	kg Neq	2.53E-03	2.52E-03	2.44E-03	4.95E-04	4.07E-04	8.09E-04	3.02E-03	2.93E-03	3.25E-03
Ozone depletion potential	kg CFC11eq	6.77E-08	4.09E-08	3.61E-08	1.07E-10	7.31E-11	1.10E-10	6.78E-08	4.09E-08	3.62E-08
Smog potential	kg O_3eq	5.49E-01	5.38E-01	5.21E-01	1.71E-01	1.49E-01	3.42E-01	7.20E-01	6.88E-01	8.63E-01
Fossil fuel consumption	MJ	1.08E+02	1.01E+02	9.88E+01	6.43E+01	4.90E+01	7.27E+01	1.72E+02	1.50E+02	1.71E+02
Eco-toxicity effect	mg	1.02E+00	1.04E+00	1.00E+00	9.66E-01	6.89E-01	1.03E+00	1.98E+00	1.73E+00	2.03E+00

To enable visual comparisons, the comparative graphical illustrations of the impact measures are also presented in Figure 7.8 and Figure 7.9. From these figures, two significant observations can be drawn. First, the performance of buildings in terms of each individual impact measure can be compared and contrasted to determine which building, and the corresponding construction method, is more environmentally responsible.

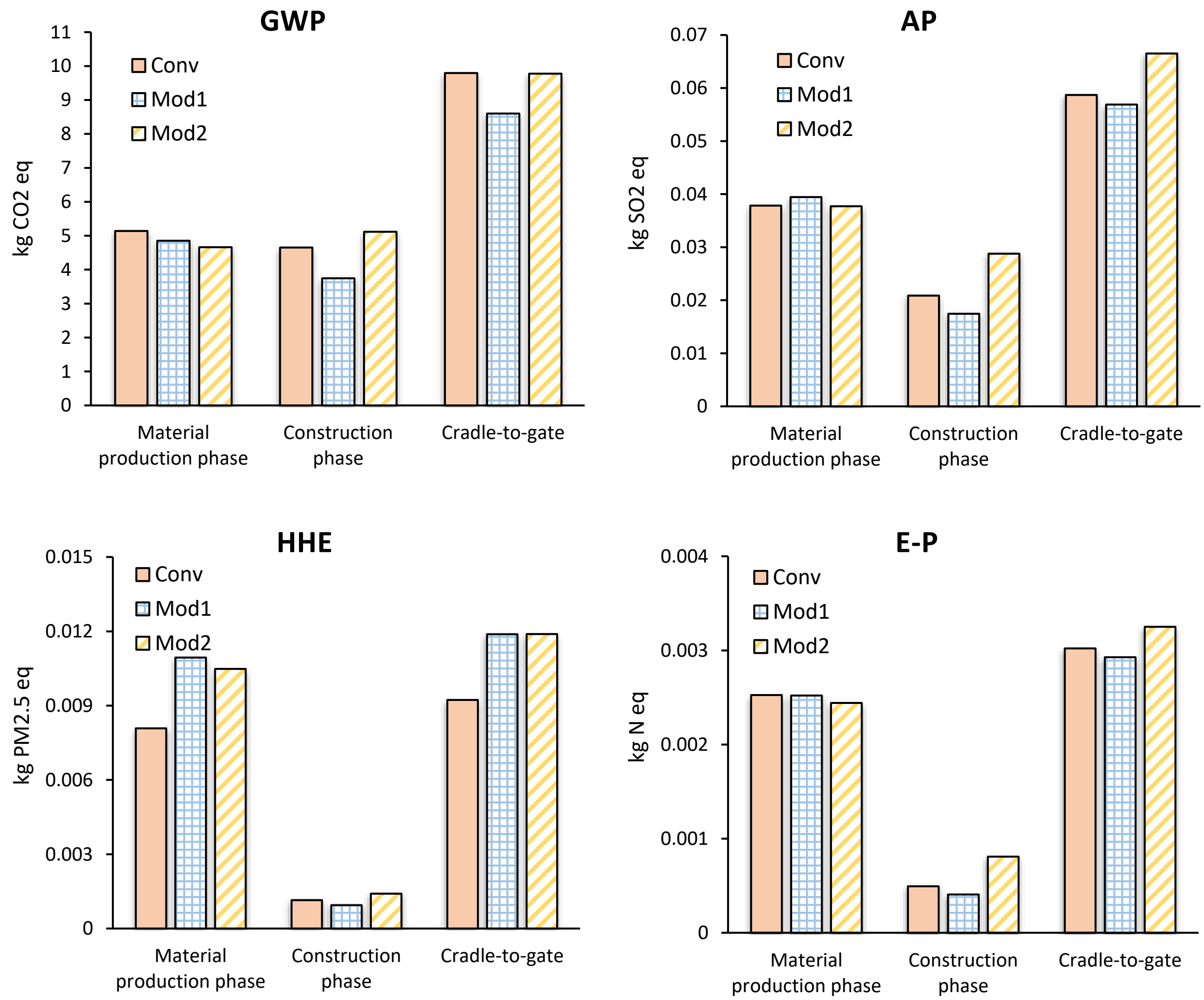

Figure 7.8 Global warming potential, Acidification potential, Human health effect, and Eutrophication potential due to construction of the benchmarking buildings

Besides, the impact contribution proportion of the material production phase and the construction phase to the overall cradle-to-gate can be realized. This latter observation is useful especially to determine the dominant phase in the case of each impact measure. For examples, the ODP contribution of the construction phase to the overall cradle-to-gate is very small compared to the material production phase (similarly, HHE). Therefore, although the ODP values in the construction phase are significantly different between the Conv, Mod1, and Mod2 buildings, the material production phase is the main source of judgment for the performances of these buildings.

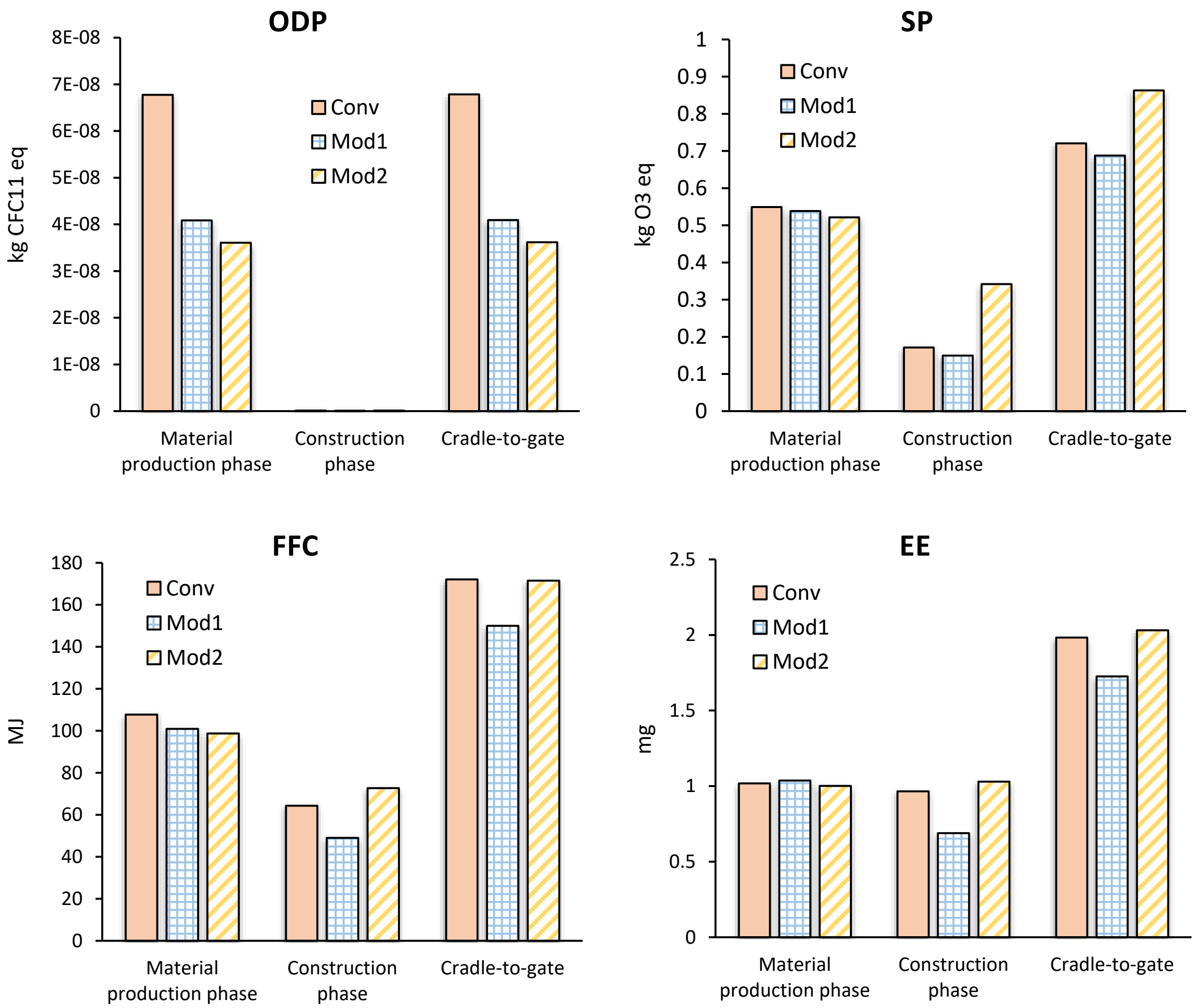

Figure 7.9 Ozone depletion potential, Smog potential, Fossil fuel consumption, and Eco-toxicity effect due to construction of the benchmarking buildings

As can be seen in Figures 7.8 and 7.9, the Mod1 building showed a better performance in terms of all impact measures compared to the Conv and Mod2 buildings in the construction phase. However, in the case of some impact measures, this building showed lower performance than Conv, Mod2, or both Conv and Mod2 in the material production phase. As mentioned above, the contribution of each impact measure to the material production phase and the construction phase can significantly influence the overall cradle-to-gate environmental performance of these buildings. Although Mod1 did not perform better than other buildings for some impact measures, it can be observed from the figures that this building still ranked first when comparing its performance over the entire cradle to gate life cycle. For example, although this building emitted more CO_2eq than Mod2 and more SO_2eq than both Conv and Mod2 in the material consumption phase, its performance in the construction phase was as high that its overall cradle-to-grate performance dominated the other two buildings (see Table 7.4 for quantities).

When it came to investigate the next priority building, it can be observed from Figures 7.8 and 7.9 that the Conv and Mod2 buildings presented comparable performance in their material production phase (except for ODP). However, in the construction phase, Conv performed marginally better than Mod2 with respect to all the impact measures which implied higher amount of energy consumption in the activity categories A3 (off-site and on-site) and A4 (material and worker transportation) of the Mod2 building. Comparison of the quantities of the impact measures during the entire cradle to gate period revealed that the Conv building performed better with respect to five impact measures including AP, HHE, EP, SP, and EE. It is important to note that in the cases of the GWP and FFC impact measures, both Conv and Mod2 performed approximately the same and the only low performing area of the Conv building is its highest ODP (ozone depletion potential) where it released almost double amount of CFC11eq compared to the Mod2 building.

While the Mod1 building that has been constructed using modular construction method proved to be the best performing building, it might initially be expected that the other modular building, i.e., Mod2, should be the next priority building. However, the above-described results showed the opposite and rejected the belief reported by some literature that the environmental impacts incurred by construction of modular buildings are always less than conventional buildings.

7.3.3 Environmental Impact Indices

The results of LCIA provided in Table 7.4, Figure 7.8, and Figure 7.9, are useful when the buildings' environmental performances with regard to individual impact measures are concerned. For example, in many cases, the climate change incurred by human activities including products, processes, or services, has been the top environmental impact concerns. Therefore, numerous LCA studies have been performed to investigate the global warming potential of different human activities as the main indicator of climate change. However, as discussed before, there are different weighting schemes developed by scientific organizations and institutes for different environmental impact categories that indicate the importance of other environmental impacts (see Table 5.12 in Chapter 5). Consequently, it becomes a more comprehensive study if more environmental impacts (where applicable and possible) are included in the study, which can provide a better insight into the environmental performance of products, processes, or services.

However, the environmental performance evaluation of different construction methods using multiple criteria (i.e., impact measures) should be carefully performed since one-by-one comparisons of the impact measures may not necessarily be capable of determining the most environmentally friendly construction option. For example, as observed and discussed above, performance comparison of the case study buildings with regard to individual impact measures did not confidently identify the higher performing building between Conv and Mod2. Although Conv performed marginally better than Mod2 concerning some of the environmental impacts, it showed much lower ODP performance. Therefore, this method of performance comparisons was not able to effectively identify the best building with overall higher environmental performance. To fill this gap, in this research, it was found useful to develop a single measure, called environmental impact index, as the representative of all included impact measures, and compare it between the case study buildings. The developed index reflects the performance of a building with respect to all the environmental impacts. To this end, as explained in Chapter 5, this research proposed an AHP-based framework by which a set of environmental impact indices was developed for each of the case study buildings. The developed indices enabled straightforward comparisons of the environmental performance of these buildings within the material production phase, construction phase, and the cradle-to-gate life cycle.

According to the methodology described in section 5.3.7.5 of Chapter 5, the normalized effects of each impact measure on the material production phase, the construction phase, and the overall cradle-to-gate were determined based on the results of LCIA (Table 7.4) as reported in Table 7.5.

Table 7.5 Environmental impact measures and their normalized effects on life cycle phases

	Material production phase (A1 & A2)			Construction phase (A3 & A4)			Cradle-to-gate (A1 - A4)		
LCA impact measures	Conv	Mod1	Mod2	Conv	Mod1	Mod2	Conv	Mod1	Mod2
Global warming potential	0.316	0.335	0.349	0.317	0.394	0.289	0.318	0.363	0.319
Acidification potential	0.338	0.324	0.339	0.342	0.409	0.248	0.343	0.354	0.303
Human health effect	0.399	0.294	0.307	0.329	0.402	0.269	0.392	0.304	0.304
Eutrophication potential	0.329	0.330	0.341	0.354	0.430	0.216	0.338	0.349	0.314
Ozone depletion potential	0.220	0.366	0.414	0.291	0.426	0.283	0.221	0.366	0.414
Smog potential	0.325	0.332	0.343	0.378	0.433	0.189	0.347	0.363	0.290
Fossil fuel consumption	0.317	0.338	0.345	0.313	0.411	0.277	0.317	0.364	0.318
Eco-toxicity effect	0.334	0.327	0.339	0.299	0.420	0.281	0.320	0.368	0.312

Through the AHP-based aggregation process, these normalized effects along with the weights of the impact measures were aggregated to develop the corresponding environmental impact indices (Equations [5.86] to [5.88] in Chapter 5). Consequently, for each of the benchmarking buildings, three indices including material production phase index (*MPPi*), construction phase index (*CPi*), and cradle-to-gate index (*CTGi*) were developed. As discussed before, to counter the human subjectivity in assigning weights for different impact measures, a sensitivity analysis was conducted where three different weighting schemes were applied and the environmental impact indices were re-developed for each building. In doing so, the aggregation process were repeated three times for all buildings by considering the EPA Science Advisory weighting, the BEES Stakeholder Panel weighting, and equal weighting (see Table 5.12). Table 7.6 presents the environmental impact indices developed for the buildings based on these weighting schemes. In addition, the *CTGi* values for the buildings based on different weighting schemes are shown in graphical form in Figure 7.10.

As seen in Table 7.6 that although different values for *MPPi*, *CPi* and *CTGi* were obtained under each weighting scheme, this did not change the rank order of the benchmarking buildings in any of the material production phase, the construction phase, and the overall cradle-to-gate.

Table 7.6 Environmental impact indices for the benchmarking buildings

	MPPi			*CPi*			*CTGi*		
Weighting schenes	Conv	Mod1	Mod2	Conv	Mod1	Mod2	Conv	Mod1	Mod2
EPA Science Advisory	0.328	0.328	0.344	0.323	0.411	0.266	0.328	0.352	0.320
BEES Stakeholder Panel	0.329	0.329	0.342	0.321	0.406	0.272	0.329	0.352	0.319
Equal weighting	0.322	0.331	0.347	0.328	0.416	0.256	0.324	0.354	0.322

The results of the *CTGi* values showed that, in all cases of the weighting schemes, the Mod1 building was the top ranked building in terms of overall cradle-to-grate performance. This confirmed the findings from comparisons of individual impact measures before. In addition, by comparing the *MPPi* and *CPi* values in Table 7.6, Mod1 was again the best performing building in both the material production phase and the construction phase.

Similar to the results of comparing individual impact measures discussed before, comparing the impact indices of the Conv and Mod2 buildings again rejected the belief that modular construction method is always the most environmentally friendly option. As seen in Figure 7.10, the Conv building showed a slightly better overall performance than the Mod2 building. However, the results of the *MPPi* and *CPi* values in Table 7.6 revealed that the Mod2 building performed better in the material production phase, while the Conv building is better within the construction phase. This indicated the fact that the design of Mod2 (e.g, assemblies, space configurations) was better than Conv (and even Mod1) so that fewer materials were used in the buildings, which required less energy in its material production phase (i.e., activity categories A1 and A2).

In contrast, the energy consumed in the construction phase of the Conv building resulted less environmental impacts than that of the Mod2 building. The collected data from the participating homebuilders showed that majority of the Mod2-builder's employees used private car for commuting to and from work (i.e., modular factory), while car-sharing and public transportation were more common in the cases of the Conv and Mod1 projects. This is necessary to remind that, the employees of a modular factory are permanent employees that commute between home and the manufacturing center all year round. Therefore, choosing more environmentally friendly commuting options can lead to less environmental burdens.

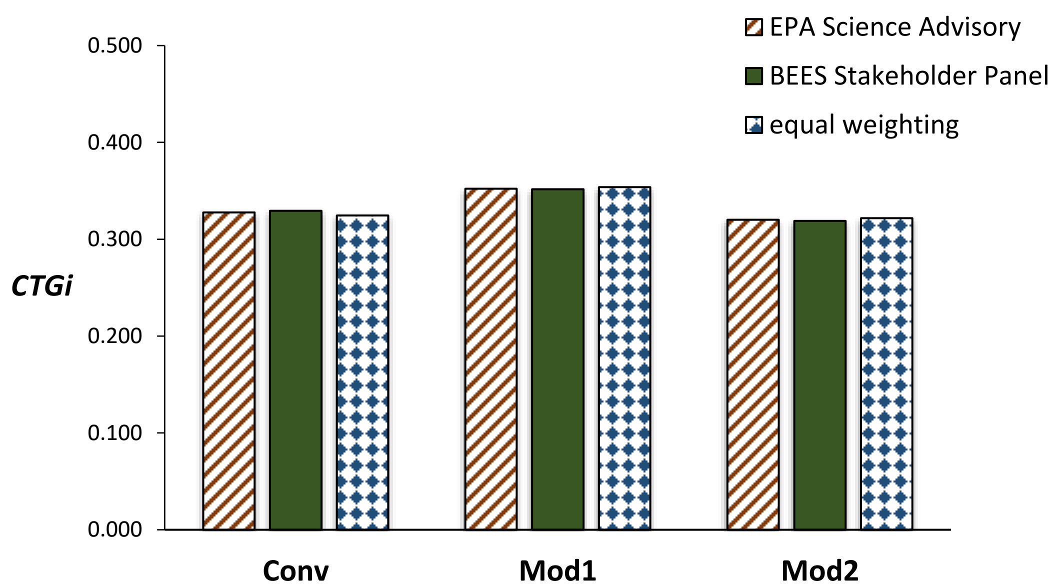

Figure 7.10 Cradle-to-grate index (*CTGi*) for different building alternatives

It is also important to mention that the total annual production of a modular factory can influence the total off-site energy consumption. The annual energy data provided by Mod1-builder and Mod2-builder revealed that the electricity and natural gas consumption per functional unit of production in the former modular factory (total annual floor area production of 408,000 ft^2) was less than that of the latter modular factory (total annual floor area production of 300,000 ft^2).

In addition to the above factors, the role of module transportation energy should not be overlooked. This factor is amongst the main differences between the conventional and modular construction methods. The final project site of a conventional building is usually within the city in which the conventional homebuilders are also located. Similarly, the on-site work of a modular building project, such as site preparation, foundation construction, and module installation of modules on foundation are usually performed by local contractors within the same city. However, the distance between the final project site of a modular building and the corresponding modular homebuilder can significantly vary, which influences on the energy required for transportation of the completed modules from the factory to the project site. Both the modular buildings in this study (Mod1 and Mod2) were located in the same city where their corresponding modular factories were also located. Thus, the module transportation effect did not play a significant role in the environmental performance of these buildings in the construction phase and subsequently in the overall cradle-to-gate. However, according to both modular builders, the project sites can be located within 300 km from the manufacturing centers.

7.4 Summary

In the first part of this chapter, the decision support framework (DSF) proposed in this research has been validated by applying it to two case study modular buildings in the Okanagan, BC (Mod1 and Mod2). Different components of the proposed DSF were carefully implemented. Using the collected data, the sustainability indices of each case study building were developed at different levels and then, they were compared to the corresponding sustainability performance scales (SPSs). Subsequently, the underperforming areas (SPCs) were realized. By conducting a sensitivity analysis, the indicators under each of the underperforming SPCs were ranked and the high contributing indicators were recognized and given high priorities for improvement actions. The results showed that both buildings performed Good and Excellent with respect to overall sustainability (Level 1) and also with respect to environmental and economic dimensions of sustainability (Level2). However, the buildings performed Poor or Moderate with respect to a number of SPCs (Level 3). Altogether, Mod1 showed better life cycle environmental and economic performances. This part of Chapter 7 showed that the implementation of the proposed DSF was straightforward and the outcome were easy to understand and interpret.

In the second part, the performance of the Mod1 and Mod2 buildings along with one conventional building (Conv) with respect to the GE SPC were evaluated. By conducting LCA, the values of eight environmental impact measures for each building were calculated and compared. In addition, a set of environmental impact indices were developed and compared, which enabled easier and confident comparison of the environmental performance of these buildings. From this part of the chapter, it was concluded that Mod1 is the most environmentally responsible building. However, comparing the impact indices of the Conv and Mod2 buildings ranked Conv higher than Mod2. This was important because it rejected the claim that modular construction method is always the most environmentally friendly option. However, the claim can be stated in a better way that modular construction has the potential to reduce the overall energy consumption which can result in less environmental burdens.

Chapter 8 Conclusions and Recommendations

In the past few decades, the construction industry has been exposed to the process of industrialization and experimenting different methods of construction. As a result, the off-site construction came into practice as an alternative to conventional on-site construction. Modular construction, as the primary method of off-site construction, has been increasingly grabbing attention in the past few years. Modular construction was claimed to offer many advantages over conventional construction and a building built using this method has been claimed to be a sustainable building.

Because of the importance of sustainability, in particular sustainable construction, it is imperative to comprehensively assess the life cycle sustainability performance of different construction methods. This can be accomplished by analyzing and comparing the sustainability performance of buildings constructed using on-site and off-site construction methods. In this regard, this research proposed a novel sustainability assessment framework for performance benchmarking of residential modular buildings. The results of this study can enhance sustainable construction by identifying the most sustainable construction options and also by improving the underperforming areas.

8.1 Summary and Conclusions

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

In Chapter 3, a thorough review was presented on existing sustainability assessment methods for buildings, potential advantages and disadvantages of modular construction, and current studies on the life cycle performance of modular buildings. The findings showed that sustainability assessment methods can be categories into systems, standards, and tools. The sustainability assessment systems were realized as the most comprehensive methods because they are capable to evaluate the sustainability of a building by choosing suitable sustainability criteria related to different TBL dimensions of sustainability and different life cycle phases. The results of the literature review also revealed that the main advantages of modular construction were higher speed of construction, better productivity and workmanship, cost savings, higher safety, higher product control and quality, and less environmental impacts. However, amongst the challenges faced by modular construction were transportation constraints, more complicated engineering and planning processes, need for more coordination and communication, higher initial investment, and more importantly, people’s negative perceptions of new construction methods. The literature review also presented that only a few studies have been quantitatively performed to compare the (environmental) performance of modular buildings and conventional buildings. This indicated the need for a comprehensive sustainability assessment framework to evaluate the life cycle performance of modular buildings with respect to the TBL sustainability dimensions. The findings of this chapter were used in identifying the research gap and in defining the research concepts and the methodologies associated with the proposed sustainability assessment framework in this research.

In Chapter 4, the TBL SPCs were compiled and the construction industry’s feedback on applicability of the SPCs for sustainability assessment of residential modular buildings was captured. Consequently, the SPCs were ranked within the associated sustainability dimension categories and an importance level ranging from ‘Extremely Low’ to ‘Extremely High’ was assigned to each SPC. Among all the 32 TBL SPCs, 26 SPCs were assigned either ‘Medium’, ‘High’, or ‘Very High’ importance criteria, which indicated that most of the SPCs are relevant and should be selected for performance assessment of modular buildings. In addition, comparing the results between different sustainability dimension categories revealed that the economic criteria still play the most significant role in distinguishing modular and conventional construction methods. Based on the results of this chapter, all SPCs with the importance level equal or higher than ‘Medium’ including 8 environmental SPCs and 9 economic SPCs were chosen for performance evaluation of residential modular buildings (the social dimension was beyond the scope of this research). It should be mentioned that although some of the selected SPCs had a level of interdependency, it was assumed that all the SPCs are independent of one another.

Chapter 5 consisted of two parts. The first part focused on quantification of the selected SPCs. In this regard, suitable measurable sustainability performance indicators (SPIs and sub-SPIs) under each SPC along with their measurement methods, their weights, their least and most desirable performance values, and corresponding ranges of data variables, were determined. The main output of this part was establishment of a performance level function (PLF) for each indicator by which it can be calculated using least data, then normalized, and represented based on a dimensionless unit of performance level (PL) between 0 and 100. Representing the calculated indicators in this way was found useful because all the indicators related to a SPC can be directly combined regardless of their original units of measurements. In addition, the PL value of an indicator indicates the closeness of the given building’s performance to the most desirable performance of the indicator (PL = 100). The second part of Chapter 5 proposed a methodology using a suitable aggregation process (TOPSIS MCDA) to develop a set of sustainability indices (between 0 and 100) for a given modular building to evaluate its performance at different levels.

The outcomes were the sustainability indices for SPCs (Level 3), each of the sustainability dimensions, i.e., environmental and economic (Level 2), and overall sustainability of the given building (Level 1). The sustainability indices at different levels enable the decision maker (DM) to focus on the desired level (i.e., Level 3, Level 2, or Level l) and investigate the performance of the building at that level using the corresponding sustainability indices.

In the first part of Chapter 6, an attempt was made to establish appropriate scales by which the developed sustainability indices of modular buildings can be compared and contrasted to their conventional counterparts. The historical performances of conventional buildings with respect to the indicators developed in the previous chapter were explored based on expert opinions and then combined using the Monte Carlo simulation method to develop the performances of these buildings with respect to the corresponding SPCs. Similarly the environmental, economic, and overall sustainability performances of conventional buildings were developed. The outcomes of this part of Chapter 6 were a set of sustainability performance scales (SPSs) for SPCs (Level 3), each of the sustainability dimensions, i.e., environmental and economic (Level 2), and overall sustainability (Level 1). The domain of each SPS ranged between 0 and 100, which was consistent with the applicable range of the developed sustainability indices and enabled easier evaluations. In addition, to provide effective and straightforward performance comparisons, the domain of each SPS was divided into four evaluation categories including Poor, Fair, Good, and Excellent performances. The sustainability performance of a given modular can be benchmarked by comparing the developed sustainability indices at the desired level (i.e., Level 3, Level 2, or Level 1) with the corresponding SPSs established in this chapter. In the second part of this chapter, all the frameworks, methodologies, and deliverables of the research, were incorporated into a single framework as an integrated decision support framework (DSF). The proposed DSF is capable of comprehensively assessing modular buildings in terms of environmental and economic performances. Since the developed DSF is a multi-level framework, the user (i.e., DM) is able to evaluate the performance of the subject modular building at each of the aforementioned levels depending on the desire and scope of the assessment study. It should be stated that, since it was not possible to establish a SPS for the GE SPC, the performance of modular buildings with respect to this SPC was evaluated using the review benchmarking method based on LCA analyses.

In Chapter 7, the proposed DSF was applied on actual case study buildings for the proof-of-concept. To this end, the life cycle sustainability performance of two case study modular buildings in the Okanagan, BC, were benchmarked by implementing different components of the developed DSF. Subsequently, the underperforming environmental and economic SPCs were realized. The results revealed that both modular buildings performed Excellent in term of overall sustainability (Level 1) and either Excellent or Good in terms of the sustainability dimensions (Level 2). However, the performance of these buildings with respect to some of the SPCs (Level 3) were shown as Fair and even Low, which indicated the need for making improvement decisions and actions to enhance the corresponding performances. By conducting a sensitivity analysis, the indicators (sub-SPIs and SPIs) under each of these SPCs were ranked and the high contributing indicators were recognized and given high priorities for improvement. In addition, a cradle-to-gate LCA was conducted for the two modular buildings and also a conventional building to examine the environmental impacts due to construction of these buildings (i.e., GE SPC). One of the modular buildings showed better performance among the three case study buildings followed by the conventional building that showed better performance than the second modular building. These findings were not fully consistent with the claim reported in the literature that construction of modular buildings is always more environmentally responsible than construction of conventional buildings. The results of the case study analyses provided a better insight into the sustainability performance of single-family modular buildings in the Okanagan, BC. In addition, the case study analyses showed that the proposed DSF is a straightforward and easy to follow framework, albeit comprehensive, that can effectively be used to promote sustainable construction.

8.2 Originality and Contribution

This research delivers the following unique contributions to the body of knowledge:

- ***Identifying the most applicable sustainability performance criteria for modular buildings:*** Numerous criteria have been used in different studies to evaluate the performance of conventional buildings. However, the primary focus has been on the environmental criteria and on specific life cycle phases of these buildings. This research developed the key performance criteria for modular buildings which covered all the TBL sustainability dimensions (i.e., environmental, economic, and social) and also all the life cycle phases of these buildings. In addition, the developed criteria were prioritized that enables the assessor to pay more attention to the top priority criteria. Furthermore, these criteria can be used in any sustainability assessment framework for modular buildings with different methodology than developed in this research.
- ***Presenting a novel method for calculating and combining quantitative and qualitative criteria:*** This research introduced the dimensionless unit of Performance Level (PL) to calculate and represent different qualitative and quantitative indicators and criteria. The

other advantage of using the PL unit is that different indicators associated with a SPC can be combined regardless of their original units. In addition, the results of combining the PLs of the indicators, i.e., the sustainability indices for the corresponding SPCs, will also be dimensionless values between 0 and 100 (similarly, the indices at upper levels), which facilitate the evaluation of a building's performance at different levels. Furthermore, the lower and upper bounds of each indicator. i.e., $PL = 0$ and $PL = 100$, have been set as the least and most desirable performances of the indicator. This means that the performance of a given building with respect to an indicator is calculated according to its benchmarks; therefore, the calculated PL of the indicator provides a deeper insight into the performance of the building.

- ***Proposing a method to explore the performance benchmarks of buildings:*** In this research, the historical performance of conventional buildings with respect to different environmental and economic criteria were developed using an innovative methodology. Since there was no database on the past performance of buildings, this research used the limited available data to determine the performance of buildings with respect to all the indicators and criteria using simulation methods. The outcomes were a set of sustainability performance scales for SPCs, sustainability dimensions, and overall sustainability that can be used as a basis to benchmark not only modular but also conventional buildings. Moreover, the proposed methodology can be used to explore the performance benchmarks of other products where there is limited data on the historical performance of them.
- ***Developing a holistic life cycle based sustainability assessment framework for modular buildings:*** This research developed an integrated sustainability assessment framework as a decision support framework (DSF) that enables modular buildings to be quantitatively evaluated. The proposed DSF can effectively identify the underperforming environmental and economic areas over the life cycle of a modular building and suggest relevant corrective actions to apply on similar projects. The DSF was developed as a multi-level assessment framework; therefore, the user can focus on one or more levels depending on the scope and aim of the performance assessment study. Implementation of the proposed DSF can assist decision makers including governments and developers with making informed decisions on the selection of the most sustainable construction methods by taking into account the regional and socio-economic circumstances. Furthermore, it can be used to address the underperforming areas over the life cycle of a modular building, even if the decision on the construction method has already been made. The presented

DSF is also a flexible such that the number and type of criteria and corresponding indicators, their measurement methods, and their benchmarks, can be updated when more information regarding the performance of conventional and modular buildings becomes available. Finally yet importantly, the methodology outlined in this research to develop the integrated sustainability assessment framework can also be adopted for assessment of other construction practices or other products and processes.

8.3 Research Limitations

Specific data collection had been a challenge in this study. A considerable amount of the required data was not available in the published literature due to the nature of this data, such as the need for local data, existing buildings' historical performance benchmarks, among others. Therefore, this research required extensive data collection from the field. A total of six surveys and several interviews and meetings have been conducted to collect the data from experts in both the construction industry and academia. This process was time-consuming and stressful because:

1) The construction industry practitioners have usually a tight schedule; therefore, it was difficult to make appointments, follow up meetings, and so forth;
2) A number of construction firms needed justifications to provide the data of their projects to be used in the case study analyses.
3) The importance of research is not well appreciated in the construction industry; therefore, only a limited number of the invited firms/expert have finally participated in the research.

The other difficulty of data collection was the need for relevant data of the social sustainability performance of buildings. The research was initially designed to address all the TBL dimensions of sustainability. However, the social dimension was eliminated due to lack of relevant data both in the literature and in the field (e.g., suitable indicators under the selected SPCs, their measurement methods, their least and most desirable performances, and so forth). Therefore, this research covered enviro-economic performance evaluation of modular buildings. However, the developed framework and corresponding methodologies are flexible enough to accommodate the data of social performance, when it becomes available in future.

The next limitation of the research was unclear interrelationships between different SPCs. In the cases of some SPCs, there was not a clear environmental and economic distinction. In other words, some economic SPCs could also be considered as environmental SPCs. Even for some SPCs within the same sustainability dimension category, there have been some overlaps. Similarly, some indicators could belong to both an environmental SPC and an economic SPC, or belong to two SPCs within the same sustainability dimension category.

Finally, there was uncertainty involved in the collected data. For example, the historical performances of conventional buildings with respect to each indicator was determined based on opinions of a limited number of experts (although experienced). Similarly, ranking of the SPCs and also the weights of the indicators, that can significantly influence the outputs, were determined based on the literature and expert opinions.

8.4 Recommendations for Future Research

For future research, following recommendations are made:

- The developed SPCs and the associated indicators provide a basis to initiate the sustainability performance assessment process of modular buildings. Consistent review and improvement of the selected SPCs and corresponding SPIs and sub-SPIs over time is recommended. The performance benchmarks of the indicators can also be updated in the future.
- The performance assessment of modular buildings in this research was designed based on comparing with the performance of similar conventional buildings. More case studies on actual modular projects are recommended to compile a database for the historical performances of modular buildings. Such database offers the additional benefit of comparisons a given modular building with other modular buildings.
- The proposed DSF suffers from the lack of the social performance assessment of modular buildings. In this research, suitable social SPCs were ranked and selected. However, if sufficient resources are available, determination of suitable indicators under each selected SPC, and establishment of corresponding PLFs and SPSs are recommended.
- A detailed investigation on the interrelationships between different SPCs and between different indicators (sub-SPIs and SPIs) is recommended. This will assist with the use of each criterion and indicator in the most relevant position and avoidance of double counting. Such interrelationships can be investigated using different methods that allow consideration of the interdependence of factors, such as the analytic network process (ANP) method.

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Appendices

Appendix A: Evaluation of SPCs against 'Applicability' and 'Measurability'

In order to identify the most appropriate SPCs for sustainability assessment of a building project, the potential SPCs should be evaluated against suitable evaluation criteria. The study described in this appendix, employs both 'Applicability' and 'Measurability' to evaluate and rank the SPCs. It should be mentioned that 'Measurability' itself consists of 'Data availability' and 'Data accuracy'.

A.1 Criteria for evaluation of SPCs

Descriptions of the evaluation criteria are as follows:

C_I – *Applicability (Relevance)*: How important and relevant is the SPC when assessing the sustainability of modular versus conventional buildings?

C_{II} – *Data Availability*: Regardless of the given SPC whether quantitative or qualitative, is the data available to measure it?

C_{III} – *Data Accuracy*: How accurate is the available data to measure the given SPC?

The relative importance weights of these criteria were determined through a group decision making process using the AHP method (Saaty 1980). The participant group consisted of a number of researchers at the University of British Columbia, Canada, who were familiar with sustainability assessment of industrial projects. A questionnaire survey was designed to facilitate experts' pairwise comparisons between the evaluation criteria. The relative importance of one criterion over the other was asked to be judged using a rating scheme ranging from 1 (Equally important) to 9 (Extremely more important). In this research, the questionnaires were delivered to and collected from participants separately; therefore, the AHP's *aggregating individual priorities* (AIP) aggregation method was used to deal with the outcomes of the survey (Forman and Peniwati 1998; Ramanathan and Ganesh 1994; Escobar and Moreno-jiménez 2007).

By implementing the AHP group decision making process, the weights of applicability, data availability, and data accuracy, were determined to be 59.65%, 20.54%, and 19.81%, respectively. This indicates that participants believed that the applicability of a SPC is more important than its measurability.

A.2 Survey implementation

The compiled environmental, economic, and social SPCs were evaluated by the construction industry experts against the evaluation criteria to rank them according to their suitability for assessing sustainability of modular buildings. Using the developed SPC categories, two questionnaire surveys, called Applicability and Measurability surveys, in this study, were designed with the help of Adobe LiveCycle Designer that provided the respondents an interactive environment. In both surveys, the objective, advantages, confidentiality, duration, completion guidance, contact information, and consent form were included. The surveys also included questions on the participant's background, such as the profession, the years of experience, and the amount of involvement in modular construction projects.

The core section of both surveys was intended to evaluate the developed SPCs with respect to the evaluation criteria. Through the Applicability survey and a number of informal interviews, the applicability (relevance) of each SPC for sustainability assessment of modular buildings was examined. In the Measurability survey, the SPCs were evaluated against data availability and data accuracy criteria. In both surveys, the SPCs and their descriptions along with the descriptions of the evaluation criteria were listed. The participants were asked to outline their preferences by scoring each SPC with respect to the evaluation criterion by comparing the sustainability of modular and conventional construction methods. In this research, ordinal scales were chosen to capture the construction professionals' opinions.

Primary construction practitioners, such as engineers, architects, construction managers, and manufacturers, as well as academically affiliated experts (originally engineers/architects) were searched as the potential participants for the first questionnaire and informal interviews. In this connection, an attempt was made to identify those practitioners that had experience in both modular and conventional building projects with focus on North American construction industry.

A.3 ELECTRE 1 MCDA method

The data collected through the surveys and interviews for scoring the SPCs against the evaluation criteria was combined with the weights of the evaluation criteria using the Elimination and Choice Translating (ELECTRE) analyses. Developed by Benayoun et al. (1966), ELECTRE method is one of the most known MCDA outranking methods that have been extensively employed in different decision making problems. The ELECTRE method has different versions. In this study, the ELECTRE 1 version was employed to analyze and rank the developed SPCs within each sustainability category. In the solution algorithm of this method, dissimilar to the other compensatory MCDA methods, weights are not viewed as the direct criteria substitution rates, but rather the absolute power of each individual criterion toward reaching the final goal, hence making the method non-compensatory (Milani et al. 2006). In addition, when an oral scale is used to evaluate criteria it might be difficult to establish preferences between different alternatives (i.e., SPCs). In such circumstances (e.g., this research), this method can resolve the problem by accumulating slight differences of scorings between different alternatives (i.e., SPCs) with regard to each evaluation criterion; hence, distinct outranking relations between different alternatives can be established (Haider et al. 2015).

In ELECTRE method, the concordance and discordance sets are produced to form outranking relationships between alternatives. In fact, the concordance and discordance sets represent the level of satisfaction and dissatisfaction of a decision maker (i.e., a survey participant in this study), respectively, when he/she gives preference to one alternative over the others (Yoon and Hwang 1995). The step-by step procedure of ELECTRE 1 is as follows:

Step 1. Normalized rating matrix

First, the normalized rating matrix is developed by using the values of alternatives with regard to attributes (i.e., the score assigned by the survey participants) as:

$$R_{ij} = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} \qquad [A.1]$$

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \text{ }, i = 1,2, \dots, m \text{ } and \text{ } j = 1,2, \dots, n \qquad [A.2]$$

Where, x_{ij} is the value of alternative *i* with respect to attribute (criterion) *j*. Since attributes can have different measurement scales, the rating matrix is normalized to enable their values to be comparable. In addition, it should be mentioned that, if an attribute is not a benefit (the more, the better) criterion, e.g., cost criterion, the value of should be reversed in the above equation.

Step 2. Weighted normalized rating matrix

The second step is to multiply the entries of the normalized matrix by the weights of corresponding attributes. Thus, the weighted normalized rating matrix is obtained as:

$$V_{ij} = \begin{bmatrix} r_{11}w_1 & \cdots & r_{1n}w_n \\ \vdots & \ddots & \vdots \\ r_{m1}w_1 & \cdots & r_{mn}w_n \end{bmatrix} \qquad [A.3]$$

Step 3. Concordance and discordance sets

As stated above, the concordance and discordance sets are formulated for each pair of alternatives A_p and A_q (p, q = 1, 2, …, m, and $p \neq q$). The concordance set includes all attributes for which A_p is preferred to A_q, can be expressed as:

$$C(p, q) = \{j | v_{pj} \geq v_{qj}\} \qquad [A.4]$$

Where v_{pj} is the weighted normalized rating of alternative A_p with respect to the jth attribute (Equation [A.3]). In other words, $C(p, q)$ is the collection of attributes where A_p is better than or equal A_q.

The discordance set, $D(p, q)$, which is the compliment of concordance set, comprises all attributes for which A_p is worse than A_q and can be stated as:

$$D(p, q) = \{j | v_{pj} < v_{qj}\} \qquad [A.5]$$

Step 4. Concordance and discordance indices

The concordance index, C_{pq}, represents the relative power of each concordance set. In other words, C_{pq} indicates the degree of confidence in the pairwise judgment of two alternatives ($A_p \rightarrow A_q$) and can be computed as:

$$C_{pq} = \sum_{j^*} w_{j^*} \qquad [A.6]$$

Where j^* are attributes included in the concordance set, i.e., $j^* \in C(p, q)$. In fact, C_{pq}, is the sum of the weights of all attributes contained in Equation [A.4].

Conversely, the discordance index (D_{pq}), represents the relative power of each discordance set and measures the degree of disagreement in pairwise judgment, $A_p \rightarrow A_q$. Two main equations have been proposed for D_{pq}. According to Yoon and Hwang (1995), D_{pq} can be calculated as:

$$D_{pq} = \frac{(\sum_{j^*} |v_{pj^*} - v_{qj^*}|)}{(\sum_{j} |v_{pj} - v_{qj}|)} \qquad [A.7]$$

Where $j \in (1, 2, \ldots, n)$ and j^* are attributes that contained in the discordance set, i.e., $j^* \in D(p, q)$.

D_{pq} can also be obtained by the following equation (Milani et al. 2006; Collette and Siarry 2003):

$$D_{pq} = \frac{max_{j^*} |v_{pj^*} - v_{qj^*}|}{max_{j} |v_{pj} - v_{qj}|} \qquad [A.8]$$

In this study, Equation [A.7] was used to calculate D_{pq} values.

Step 5. Outranking relationships

The power of the dominance relationship of alternative A_p over alternative A_q depends on how high is the concordance index (C_{pq}) and how low is the discordance index (D_{pq}). The outranking relationships are built by comparing the concordance and discordance indices with specified limits (thresholds) for concordance and discordance. In fact, A_p outranks A_q if:

$$C_{pq} \geq c \qquad \text{[A.9]}$$

and

$$D_{pq} < d \qquad \text{[A.10]}$$

Where c and d are the concordance and discordance thresholds, respectively. The more severe the threshold values, the more difficult it is to pass the tests. The values of c and d can be calculated based on the results of C_{pq} and D_{pq}, or constant values chosen by the decision maker/analyst. For example, Yoon and Hwang (1995) defined c and d as the averages of C_{pq} and D_{pq} values, respectively, while Collette and Siarry (2003) suggested $c = 0.7$ and $d = 0.3$.

By defining the threshold values c and d, the outranking relationships between alternatives can be established. However, the impact of the selected threshold values upon the ultimate ranking can be significant and this is one of the weaknesses of the ELECTRE 1 method (Yoon and Hwang 1995). Therefore, to avoid defining the threshold values, a complementary version of ELECTRE 1 was introduced by Van Delft and Nijkamp (1976) by defining net concordance and net discordance indices for each alternative. The net concordance and discordance indices provide an effective numerical measure to sort all the alternatives from the best to the worst (Haider et al. 2014). The complementary analysis of the ELECTRE 1 method is described below as the last step of the calculations.

Step 6. Net outranking relationships for ranking the alternatives

As stated above, through this last step, the overall ranks of alternatives are established using the net outranking relationships; therefore, the selection process of suitable alternatives becomes easier. The net outranking relationships are obtained by calculating the net concordance and the net discordance indices for each alternative. The net concordance index (C_p) estimates the degree to which the dominance of an alternative (e.g., A_p) over all other alternatives exceeds the dominance of other alternatives over the given alternative. C_p can be computed as: thereof

$$C_p = \sum_{k=1}^{m} C_{pk} - \sum_{k=1}^{m} C_{kp}; \qquad k \neq p \qquad \text{[A.11]}$$

Similarly, the net discordance (D_p) indicates the relative feebleness of an alternative with regard to the others and can be calculated as:

$$D_p = \sum_{k=1}^{m} D_{pk} - \sum_{k=1}^{m} D_{kp}; \qquad k \neq p \qquad \text{[A.12]}$$

By calculating and checking the values of C_p *and* D_p for all the alternatives, the net outranking relationships can be developed and thereof final ranking of the alternatives is established.

Namely, the higher C_p and lower D_p values control the final ranking order of the alternatives. In other words, the alternative with the maximum C_p and minimum D_p values is the most preferred alternative, and the other alternatives are ranked accordingly.

A.4 Ranking the SPC categories

As stated earlier, the data collected from the surveys along with the weights of the evaluation criteria were analyzed to rank the SPCs. The ELECTRE 1 steps were carefully followed for each sustainability category to separately determine the overall rank of the environmental, economic, and social SPCs.

The overall rank order of each SPC within the environmental, economic, and social categories are presented in Table A.1, Table A.2, and Table A.3, respectively. Each SPC was ranked within its associated category based on its net concordance and net discordance indices (C_p *and* D_p). In the cases of some SPCs such as EP, the ranking of net concordance and net discordance are consistent (identical); therefore, finding the overall rank order of these SPCs is not difficult. However, some discrepancies were recognized in the cases of other SPCs as their net concordance ranks were different from their net discordance ranks (e.g., CWM and MCC); consequently, this is a challenge to determine the final ranking of these criteria. Following the step 6 of ELECTRE method above, this issue can be addressed by plotting the SPCs using their net concordance vs. net discordance values, as shown in Figure A.1a. By projecting the SPCs on the -45° line, and eventually, calculating the distance of the projected points from the origin, final ranking of alternatives can be obtained. For those SPCs located in the fourth quadrant, higher distances means better ranks. Contrary, in the cases of SPCs located in the second quadrant, lower distances indicate better ranks. Hence, by calculating and comparing these distances, all the SPCs alternatives were ranked as reflected in the last column of Table A.1.

Similarly, based on the values of C_p *and* D_p indices, the economic SPCs were ranked (Table A.2 and Figure A.1b). Despite the environmental SPCs, almost all the economic SPCs were consistent in terms of their C_p and D_p rankings (except DB and IM).

In the case of the social category, for majority of the social SPCs, the net concordance and net discordance rankings were identical. The only inconsistencies were noted in AB and ILE. The final ranking of these two SPCs were determined by using Figure A.1c and comparing the distance of each SPC from the origin.

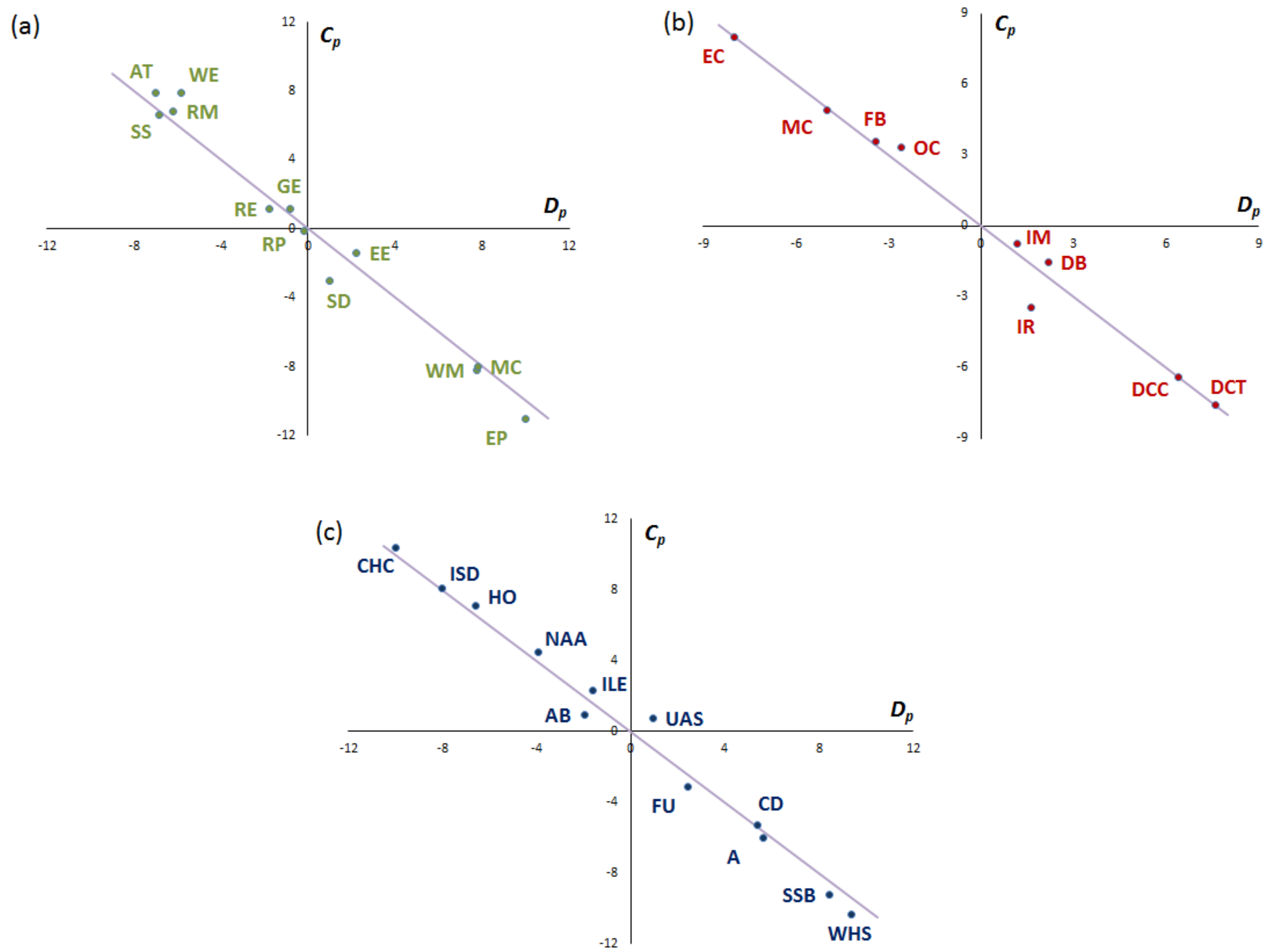

Figure A.1 Net Concordance (C_p) and net discordance (D_p) indices for SPCs; (a) Environmental category; (b) Economic category; (c) Social category. Reproduced from Kamali et al. (2018). Used with permission from © Elsevier

Table A.1 Net outranking of the environmental sustainability performance criteria

SPC	C_p	D_p	Ranking of C_p	Ranking of D_p	Final ranking of SPC
Energy performance and efficiency strategies (EP)	9.807	-10.773	1	1	1
Construction waste management (CWM)	7.772	-8.178	3	2	2
Material consumption in construction (MCC)	7.807	-8.008	2	3	3
Site disruption and appropriate strategies (SD)	0.983	-3.014	4	4	4
Renewable & environmentally preferable products (REP)	-0.174	-0.127	5	5	5
Greenhouse gas emissions (GE)	-0.840	1.145	6	7	6
Renewable energy use (RE)	-1.772	1.139	7	6	7
Regional (local) materials (RM)	-6.176	6.837	9	9	8
Site selection (SS)	-6.809	6.645	10	8	9
Water and wastewater efficiency strategies (WE)	-5.832	7.860	8	10	10
Alternative transportation (AT)	-6.994	7.876	11	11	11

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Table A.2 Net outranking of the economic sustainability performance criteria

SPC	C_p	D_p	Ranking of C_p	Ranking of D_p	Final ranking of SPC
Design and construction time (DCT)	7.604	-7.583	1	1	1
Design and construction costs (DCC)	6.396	-6.417	2	2	2
Investment and related risks (IRR)	1.614	-3.478	4	3	3
Durability of building (DB)	2.203	-1.540	3	4	4
Integrated management (IM)	1.186	-0.736	5	5	5
Operational costs (OC)	-2.587	3.333	6	6	6
Adaptability of building (AB)	-3.420	3.564	7	7	7
Maintenance costs (MC)	-4.995	4.875	8	8	8
End of life costs (EC)	-8.000	8.000	9	9	9

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Table A.3 Net outranking of the social sustainability performance criteria

SPC	C_p	D_p	Ranking of C_p	Ranking of D_p	Final ranking of SPC
Workforce health and safety (WHS)	9.386	-10.360	1	1	1
Safety and security of building (SSB)	8.418	-9.238	2	2	2
Affordability (A)	5.619	-6.038	3	3	3
Community disturbance (CD)	5.361	-5.292	4	4	4
Functionality and usability of the physical space (FU)	2.409	-3.119	5	5	5
User acceptance and satisfaction (UAS)	0.965	0.760	6	6	6
Aesthetic options and beauty of the building (ABB)	-1.980	0.935	8	7	7
Influence on the local economy (ILE)	-1.600	2.330	7	8	8
Neighborhood accessibility and amenities (NAA)	-3.953	4.491	9	9	9
Health, comfort and well-being of occupants (HO)	-6.599	7.078	10	10	10
Influence on local social development (ISD)	-8.012	8.080	11	11	11
Cultural and heritage conservation (CHC)	-10.002	10.372	12	12	12

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As an example, the ELECTRE calculations for the economic SPC category have been included in the following section.

A.5 Calculation example for final ranking of the economic SPCs

Based on the literature review, interviews, and screening process, 9 SPCs were selected as potential representatives of the economic sustainability. Then, the construction experts evaluated these SPCs against applicability, data availability, and data accuracy. Table A.4 shows the resulting rating matrix. As stated in Section 2.1.2 of this main manuscript, the weights of the evaluation criteria were allocated using a group decision making process and AHP method. Accordingly, the normalized weighted rating matrix was developed using Equations [A.1], [A.2], and [A.3] as presented in Table A.5.

Table A.4 The rating matrix for the economic category

SPC	Applicability (C_I)	Data availability (C_{II})	Data accuracy (C_{III})
Design and construction time (DCT)	4.37	2.41	2.38
Design and construction costs (DCC)	4.32	2.35	2.41
Operational costs (OC)	3.80	1.88	1.88
Maintenance costs (MC)	3.73	1.82	1.94
End of life costs (EC)	3.32	1.65	1.59
Durability of building (DB)	3.93	1.94	1.94
Investment and related risks (IRR)	3.85	2.18	2.19
Adaptability of building (AB)	3.78	1.76	2.00
Integrated management (IM)	3.88	1.88	2.00

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Table A.5 The normalized weighted rating matrix for the economic category

SPC	Applicability (C_I)	Data availability (C_{II})	Data accuracy (C_{III})
Weights of the evaluation criteria (%)	59.65	20.54	19.81
Design and construction time (DCT)	0.223	0.082	0.076
Design and construction costs (DCC)	0.220	0.080	0.078
Operational costs (OC)	0.194	0.064	0.061
Maintenance costs (MC)	0.190	0.062	0.063
End of life costs (EC)	0.169	0.056	0.051
Durability of building (DB)	0.200	0.066	0.063
Investment and related risks (IRR)	0.197	0.074	0.070
Adaptability of building (AB)	0.193	0.060	0.064
Integrated management (IM)	0.198	0.064	0.064

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Using the normalized weighted values of the SPCs (Table A.5), Equation [A.4], and Equation [A.5], the concordance and discordance sets are obtained as shown in Tables A.6 and A.7.

In the next step, using Equation [A.6], Equation [A.7], and the results of concordance and discordance sets, the concordance and discordance indices were developed for all the SPCs and presented in Tables A.8 and A.9.

Table A.6 The concordance sets for SPCs in the economic category

C (1,2) = {1,2}	C (2,1) = 3	C (3,1) = 0	C (4,1) = 0	C (5,1) = 0	C (6,1) = 0	C (7,1) = 0	C (8,1) = 0	C (9,1) = 0
C (1,3) = {1,2,3}	C (2,3) = {1,2,3}	C (3,2) = 0	C (4,2) = 0	C (5,2) = 0	C (6,2) = 0	C (7,2) = 0	C (8,2) = 0	C (9,2) = 0
C (1,4) = {1,2,3}	C (2,4) = {1,2,3}	C (3,4) = {1,2}	C (4,3) = {3}	C (5,3) = 0	C (6,3) = {1,2,3}	C (7,3) = {1,2,3}	C (8,3) = {3}	C (9,3) = {1,2,3}
C (1,5) = {1,2,3}	C (2,5) = {1,2,3}	C (3,5) = {1,2,3}	C (4,5) = {1,2,3}	C (5,4) = 0	C (6,4) = {1,2,3}	C (7,4) = {1,2,3}	C (8,4) = {1,3}	C (9,4) = {1,2,3}
C (1,6) = {1,2,3}	C (2,6) = {1,2,3}	C (3,6) = 0	C (4,6) = {3}	C (5,6) = 0	C (6,5) = {1,2,3}	C (7,5) = {1,2,3}	C (8,5) = {1,2,3}	C (9,5) = {1,2,3}
C (1,7) = {1,2,3}	C (2,7) = {1,2,3}	C (3,7) = 0	C (4,7) = 0	C (5,7) = 0	C (6,7) = {1}	C (7,6) = {2,3}	C (8,6) = {3}	C (9,6) = {3}
C (1,8) = {1,2,3}	C (2,8) = {1,2,3}	C (3,8) = {1,2}	C (4,8) = {2}	C (5,8) = 0	C (6,8) = {1,2}	C (7,8) = {1,2,3}	C (8,7) = 0	C (9,7) = {1}
C (1,9) = {1,2,3}	C (2,9) = {1,2,3}	C (3,9) = {2}	C (4,9) = 0	C (5,9) = 0	C (6,9) = {1,2}	C (7,9) = {2,3}	C (8,9) = {3}	C (9,8) = {1,2,3}
C (1,2) = {1,2}	C (2,1) = 3	C (3,1) = 0	C (4,1) = 0	C (5,1) = 0	C (6,1) = 0	C (7,1) = 0	C (8,1) = 0	C (9,1) = 0

Table A.7 The discordance sets for SPCs in the economic category

D (1,2) = {3}	D (2,1) = {1,2}	D (3,1) = {1,2,3}	D (4,1) = {1,2,3}	D (5,1) = {1,2,3}	D (6,1) = {1,2,3}	D (7,1) = {1,2,3}	D (8,1) = {1,2,3}	D (9,1) = {1,2,3}
D (1,3) = 0	D (2,3) = 0	D (3,2) = {1,2,3}	D (4,2) = {1,2,3}	D (5,2) = {1,2,3}	D (6,2) = {1,2,3}	D (7,2) = {1,2,3}	D (8,2) = {1,2,3}	D (9,2) = {1,2,3}
D (1,4) = 0	D (2,4) = 0	D (3,4) = {3}	D (4,3) = {1,2}	D (5,3) = {1,2,3}	D (6,3) = 0	D (7,3) = 0	D (8,3) = {1,2}	D (9,3) = 0
D (1,5) = 0	D (2,5) = 0	D (3,5) = 0	D (4,5) = 0	D (5,4) = {1,2,3}	D (6,4) = 0	D (7,4) = 0	D (8,4) = {2}	D (9,4) = 0
D (1,6) = 0	D (2,6) = 0	D (3,6) = {1,2,3}	D (4,6) = {1,2}	D (5,6) = {1,2,3}	D (6,5) = 0	D (7,5) = 0	D (8,5) = 0	D (9,5) = 0
D (1,7) = 0	D (2,7) = 0	D (3,7) = {1,2,3}	D (4,7) = {1,2,3}	D (5,7) = {1,2,3}	D (6,7) = {2,3}	D (7,6) = {1}	D (8,6) = {1,2}	D (9,6) = {1,2}
D (1,8) = 0	D (2,8) = 0	D (3,8) = {3}	D (4,8) = {1,3}	D (5,8) = {1,2,3}	D (6,8) = {3}	D (7,8) = 0	D (8,7) = {1,2,3}	D (9,7) = {2,3}
D (1,9) = 0	D (2,9) = 0	D (3,9) = {1,3}	D (4,9) = {1,2,3}	D (5,9) = {1,2,3}	D (6,9) = {3}	D (7,9) = {1}	D (8,9) = {1,2}	D (9,8) = 0
D (1,2) = {3}	D (2,1) = {1,2}	D (3,1) = {1,2,3}	D (4,1) = {1,2,3}	D (5,1) = {1,2,3}	D (6,1) = {1,2,3}	D (7,1) = {1,2,3}	D (8,1) = {1,2,3}	D (9,1) = {1,2,3}

Table A.8 The concordance index for SPCs in the economic category

C_{pq}	1	2	3	4	5	6	7	8	9
1	-	0.802	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.198	-	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3	0.000	0.000	-	0.802	1.000	0.000	0.000	0.802	0.205
4	0.000	0.000	0.198	-	1.000	0.198	0.000	0.205	0.000
5	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000
6	0.000	0.000	1.000	1.000	1.000	-	0.597	0.802	0.802
7	0.000	0.000	1.000	1.000	1.000	0.404	-	1.000	0.404
8	0.000	0.000	0.198	0.795	1.000	0.198	0.000	-	0.198
9	0.000	0.000	1.000	1.000	1.000	0.198	0.597	1.000	-

Table A.9 The discordance index for SPCs in the economic category

D_{pq}	1	2	3	4	5	6	7	8	9
1	-	0.208	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.792	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	1.000	1.000	-	0.248	0.000	1.000	1.000	0.418	1.000
4	1.000	1.000	0.752	-	0.000	1.000	1.000	0.685	1.000
5	1.000	1.000	1.000	1.000	-	1.000	1.000	1.000	1.000
6	1.000	1.000	0.000	0.000	0.000	-	0.811	0.123	0.296
7	1.000	1.000	0.000	0.000	0.000	0.189	-	0.000	0.072
8	1.000	1.000	0.582	0.315	0.000	0.877	1.000	-	1.000
9	1.000	1.000	0.000	0.000	0.000	0.704	0.928	0.000	-

Using the concordance and discordance indices, Equation [A.11] and Equation [A.12], the net concordance index (*Cp*) and net discordance index (*Dp*) for all the SPCs were calculated; consequently, the net outranking relationships were developed. The net concordance and discordance indices and the net outranking of the economic sustainability performance criteria have presented earlier in this appendix (Table A.2) and not repeated here.

A.6 Sensitivity analysis

In addition to the weight set assigned through the AHP-based group decision making process (WS_{GDM}), two additional hypothetical weight sets were applied to examine the sensitivity of the SPC ranking results to the weights of the evaluation criteria as:

- WS_1: applicability (70%), data availability (15%), data accuracy (15%)
- WS_2: applicability (50%), data availability (25%), data accuracy (25%)

Compared to WS_{GDM} (i.e., applicability: 59.65%, data availability: 20.54%, and data accuracy:

19.81%), in WS_1, more weight was assigned to the applicability criterion, contrary to the case of WS_2 where the weights of data availability and data accuracy criteria were increased. Results of repeating the ELECTRE analyses for each sustainability category using the three different weight sets are presented in Figure A.2.

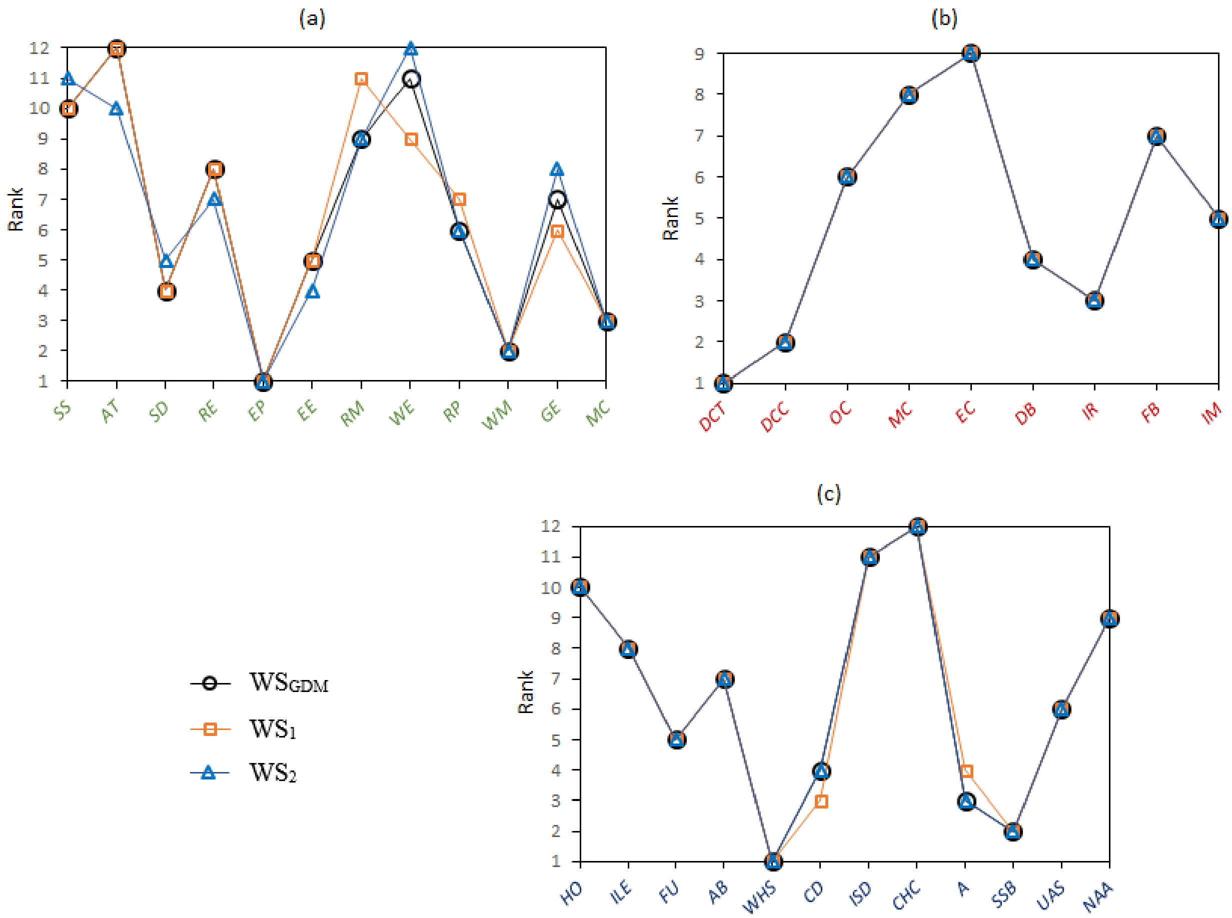

Figure A.2 Net outranking of (a) Environmental category; (b) Economic category; (c) Social category, for different weight sets of the evaluation criteria. Reproduced from Kamali et al. (2018). Used with permission from © Elsevier

It can be seen from the net outranking of the SPCs that changing the established weights of the evaluation criteria (WS_{GDM}) within at least the defined range (WS_1↔WS_2), does not affect the rankings of the economic and social SPCs (FigureA.2b and Figure A.2c). In other words, all the economic and social SPCs were assigned identical ranks using the three weight sets except CD and A with rank orders of third and fourth for WS_1 (they are fourth and third, respectively, for both WS_{GDM} and WS_2).

In contrast, as Figure A.2a demonstrates, there are some minor discrepancies between the environmental SPC rankings when using the different weight sets. Yet, these inconsistencies cannot be significant because (1) all the SPC rankings follow the same trend, which means when switching from a WS to another, the rank order of a SPC changed locally; and (2) there is no change in the rank order of the top priority SPCs (i.e., EP, CWM, and MC) for all three WSs.

Appendix B: First Step Study

In this appendix, the results of the first step study to estimate population variances for sample size determination of Survey A including the respondents' scores and the standard deviations for the environmental, economic, and social SPC categories are presented.

Table B.1 Standard deviations (σ) of scores for the environmental SPC category

Sample #	Score of SPC										
	SS	**AT**	**SD**	**RE**	**EP**	**WE**	**RM**	**REP**	**CWM**	**GE**	**MCC**
1	3	2	2	3	4	3	2	3	3	3	5
2	2	4	2	4	4	3	4	4	5	4	5
3	3	2	5	3	5	3	3	3	3	2	3
4	4	4	4	3	4	4	4	4	5	4	4
5	4	3	4	5	4	4	3	4	4	4	3
6	3	2	4	5	4	3	5	3	4	4	2
7	2	2	4	3	4	2	4	4	5	3	4
8	3	4	4	3	3	2	3	3	5	3	4
9	3	4	5	2	4	4	3	3	4	3	3
10	3	2	3	4	4	3	3	4	5	5	4
11	4	3	4	3	5	4	5	4	4	4	4
12	3	3	4	3	3	3	2	3	3	4	5
13	2	3	4	3	5	1	4	3	5	5	5
σ	0.71	0.86	0.93	0.87	0.64	0.91	0.96	0.52	0.83	0.85	0.95

Table B.2 Standard deviations (σ) of scores for the economic SPC category

Sample #	Score of SPC								
	DCT	**DCC**	**OC**	**MC**	**EC**	**DB**	**IRR**	**AB**	**IM**
1	5	5	3	3	3	3	4	3	3
2	5	5	4	4	3	5	5	5	5
3	4	4	4	4	3	3	3	3	3
4	4	4	4	3	3	4	4	3	4
5	4	3	4	3	3	4	4	3	5
6	5	4	4	2	5	4	4	5	5
7	5	5	3	3	3	4	4	4	4
8	5	4	3	3	5	3	4	2	4
9	4	4	3	3	2	4	2	4	3
10	5	5	5	3	3	5	4	4	4
11	4	4	4	5	5	5	4	4	3
12	5	4	1	1	3	2	4	2	3
13	5	5	3	3	3	5	4	3	5
σ	0.51	0.63	0.96	0.95	0.96	0.95	0.69	0.96	0.86

Table B.3 Standard deviations (σ) of scores for the social SPC category

Sample #	Score of SPC											
	HO	**ILE**	**FU**	**ABB**	**WHS**	**CD**	**ISD**	**CHS**	**A**	**SSB**	**UAS**	**NAA**
1	5	3	3	3	5	4	2	3	4	4	4	3
2	4	4	4	4	5	4	4	4	4	5	5	4
3	4	3	3	3	3	3	3	3	4	4	3	3
4	4	4	4	4	4	4	4	4	4	4	4	4
5	3	2	3	3	4	3	2	3	5	5	3	2
6	5	5	3	5	5	5	3	1	5	5	5	3
7	3	4	2	3	4	4	3	3	3	4	3	3
8	3	4	3	4	5	4	3	3	3	4	3	3
9	4	3	4	4	5	4	4	3	3	5	4	4
10	3	3	4	4	5	5	4	1	3	5	2	5
11	5	4	4	5	4	4	3	4	5	4	4	4
12	3	3	4	2	5	4	3	3	4	3	2	3
13	5	4	4	4	5	5	3	3	4	5	4	3
σ	0.86	0.78	0.66	0.85	0.66	0.64	0.69	0.95	0.76	0.65	0.96	0.77

Appendix C: TOPSIS MCDA Method

In this appendix, the step-by step procedure of the TOPSIS MCDA method used in this research has been described (adapted from Yoon and Hwang (1995)).

Step 1. Weights of SPIs

The relative importance weights of the sustainability performance indicators (SPIs) under each sustainability performance criterion (SPC) should be determined.

Step 2. Normalized SPIs

Once the SPIs are calculated (performance score or x_{ij}), if the x_{ij} values are not already normalized, they need to be normalized (r_{ij}). The vector normalization can be used for normalization:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad i = 1, \dots, m \quad j = 1, \dots, n \qquad \text{[C.1]}$$

Step 3. Weighted normalized matrix

The weighted normalized matrix should be developed. The weighted normalized performance score of each SPI is calculated as:

$$v_{ij} = w_j r_{ij} \qquad \text{[C.2]}$$

where w_j = corresponding weight of that SPI.

Step 4. Positive-Ideal and Negative-Ideal Solutions

In this step, the positive-ideal solution (PIS) and negative-ideal solution (NIS) are identified. X^+ and X^- are defined as the PIS and NIS, respectively, in terms of weighted performance scores as follows:

$$X^+ = \{v_1^+, v_2^+, \dots, v_j^+, \dots, v_n^+\} = \{(max_i v_{ij} | j \epsilon J_1), (min_i v_{ij} | j \epsilon J_2), i = 1,2, \dots, m\} \qquad \text{[C.3]}$$

$$X^- = \{v_1^-, v_2^-, \dots, v_j^-, \dots, v_n^-\} = \{(min_i v_{ij} | j \epsilon J_1), (max_i v_{ij} | j \epsilon J_2), i = 1,2, \dots, m\} \qquad \text{[C.4]}$$

where J_1 = set of benefit attributes; and J_2 = set of cost attributes.

Step 5. Separation measures

In this step, the distance of the subject building from PIS and NIS values (i.e., separation measures) is calculated. The distances of all the performance levels of SPIs associated with a SPC are measured using the n-dimensional Euclidean distance. The separation measure of each SPC from the PIS can be calculated as:

$$S_i^+ = \sqrt{\sum_{i=1}^{n}\left(v_{ij} - v_j^+\right)^2},\ i = 1,2,\dots,m \qquad \text{[C.5]}$$

and separation measure of each SPC from the NIS can be calculated as

$$S_i^- = \sqrt{\sum_{i=1}^{n}\left(v_{ij} - v_j^-\right)^2},\ i = 1,2,\dots,m \qquad \text{[C.6]}$$

Step 6. Aggregated indices

The aggregated sustainability indices for each SPC (e.g., *PEi*, *CWMi*) is developed by calculating similarities to PIS as:

$$SPCi = \frac{S_i^-}{S_i^- + S_i^+} \qquad \text{[C.7]}$$

Similarly, the sustainability indices can be calculated for sustainability dimensions and the overall sustainability.

Appendix D: Establishment of a Suitable PLF for 'Construction waste reuse'

Although many studies mentioned that 'reuse' is an important CWM strategy, rare studies provided the quantification and evaluation of the strategy in a building project. Green Globes is one of the rating systems that addressed the reuse of buildings' parts and components. It classified and scored the 'reuse' implementation according to the reused elements and components of an existing building in a new building project (GBI 2014; GBI 2015). However, this classification and evaluation standards have been provided for multi-family residential multifamily buildings (EPA 2018b). Therefore, the provided standards have been adjusted to fit single-family buildings with the help of experts in this research. A total of three sub-SPIs have been recognized for this SPI: 'CWM3-1 Reuse of façades', 'CWM3-2 Reuse of structural systems', and 'CWM3-3 Reuse of non-structural elements'.

Reuse of façades (CWM3-1)

This sub-SPI addresses the reuse the existing building's façades at the end of its lifetime in another building projects. The percentage of the façade from an existing building that is retained and incorporated in the new building design is calculated as (GBI 2015):

$$ReFa = 100 \times A/B \qquad [D.1]$$

Where *ReFa* is the percentage of the reused façade, *A* is the area of retained façade reused in the new building, and *B* is the total area of the new building's façade.

A building shows its least and best performances with respect to this sub-SPI when the *ReFa* came to be 10% and 50%, respectively. Therefore, the PLF to calculate the performance level of CWM3-1 is:

$$PL_{CWM3\text{-}1} = 250(ReFa) - 25 \qquad 10\% \leq ReFa \leq 50\% \qquad [D.2]$$

Reuse of structural systems (CWM3-2)

Structural systems refer to the load-resisting system of a building (other than the building envelope) that transfers loads to the foundation though interconnected structural components or members. In some cases, the structural systems of the existing building at the end of its life can be retained and reused in another building project. The percentage of the reused structural components or members in a new building design can be calculated as (GBI 2015):

$$ReSt = 100 \times A/B \qquad [D.3]$$

Where *ReSt* is the percentage of the reused structural systems, *A* is the volume of the reused structural components or members in the new building, and *B* is the total volume of the new building's structural systems.

A building shows its least and best performances with respect to this CWM3-2 when the *ReSt* reaches 10% and 60%, respectively. Therefore, the PLF to calculate the performance level of the sub-SPI is presented as:

$$PL_{CWM3\text{-}2} = 200(ReSt) - 20 \qquad 10\% \leq ReSt \leq 60\% \qquad \text{[D.4]}$$

Reuse of non-structural elements (CWM3-3)

CWM3-3 seeks the reuse of the existing non-structural elements such as interior ceilings, interior partitions, furnishings and/or demountable walls, in a new building design.

The percentage of the reused non-structural elements in a new building design can be calculated as (GBI 2015):

$$ReNSt = 100 \times A/B \qquad \text{[D.5]}$$

Where *ReNSt* is the percentage of the reused structural systems, *A* is the area of the reused non-structural elements in the new building, and *B* is the total area of the non-structural element in the new building. Areas are calculated as the projected area of the element. For example, if an interior partition is re-used, the area is calculated as length × height of the wall.

Similar to the case of the previous sub-SPI, the new building performs excellent with respect to this sub-SPI by incorporating up to 60% non-structural elements from the older projects. Subsequently, the following PLF can be used to calculate the performance level of CWM3-3:

$$PL_{CWM3\text{-}3} = 200(ReNSt) - 20 \qquad 10\% \leq ReNSt \leq 60\% \qquad \text{[D.6]}$$

The performance level of the parent CWM3 SPI is calculated based on the performance levels of the three associated sub-SPIs and their weights. The weights of CWM3-1, CWM3-2, and CWM3 have been determined as 0.374, 0.313, and 0.313, respectively (GBI 2015). Thus, the following PLF was can be used to calculate CWM3 performance of the subject building:

$$PL_{CWM3} = 0.374 \times PL_{CWM3\text{-}1} + 0.313 \times PL_{CWM3\text{-}2} + 0.313 \times PL_{CWM3\text{-}3} \qquad \text{[D.7]}$$

Appendix E: Renewable Energy Sources and Net-zero Energy Buildings

Renewable energy is derived from natural processes that are replenished at an equal or faster rate than the rate at which they are consumed (except biomass). There are various forms of renewable energy, deriving directly or indirectly from the sun or from heat generated deep within the earth (NRC 2017d). There are five commonly used renewable energy sources (EIA 2018):

- Biomass. Biomass is organic material that comes from plants and animals. Biomass contains stored energy from the sun. Plants absorb the sun's energy in a process called photosynthesis. The chemical energy in plants is passed to animals and people after the plants are consumed. The biomass source includes wood and wood waste, municipal solid waste, landfill gas and biogas, ethanol, and biodiesel.
- Hydropower. Hydropower is electricity produced from flowing water. Hydropower is the largest renewable energy source for electricity generation in the US.
- Geothermal. Geothermal energy is heat from within the earth. This heat can be recovered as steam or as hot water, and it can be used to heat buildings or to generate electricity.
- Wind. Today, wind energy is mainly used to generate electricity energy.
- Solar. Solar energy systems use radiation from the sun to produce heat and electricity. There are three basic categories of solar energy systems: solar thermal systems, solar thermal-electric power plants, and photovoltaic systems.

Renewable energy plays an important role in reducing greenhouse gas emissions. When renewable energy sources are used, the demand for finite fossil fuels is reduced. Unlike fossil fuels, non-biomass renewable sources of energy (i.e., hydropower, geothermal, wind, and solar) do not directly emit greenhouse gases (NEB 2017; EIA 2018). However, the use of renewable energy is still limited. For example, about 11% of the total US energy consumption was supplied by renewable energy sources in 2017 as shown in Figure E.1 (EIA 2018).

A wide range of energy-producing technologies and equipment has been developed over time to take advantage of these natural resources. As a result, usable energy can be produced in the form of electricity, industrial heat, thermal energy for space and water conditioning, and transportation fuels (NRC 2017c). In the case of buildings, renewable energies can be used for space heating, water heating, and electricity (e.g., lighting, appliances) (NRC 2017c).

The known concept of net-zero energy building (NZEB) (also known as zero-energy building or zero net energy) is used as a benchmark building in terms of using renewable energy sources. In a NZEB, the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy created on the site or by renewable energy sources elsewhere

(Pless and Torcellini 2010; Peterson et al. 2015; Torcellini et al. 2006).

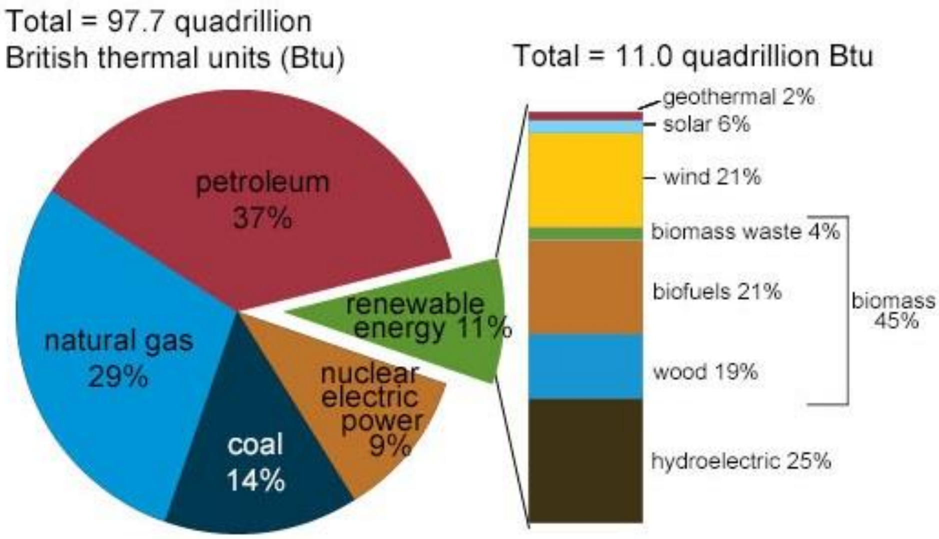

Figure E.1 US energy consumption by energy source in 2017. Reproduced from EIA (2018). Used with permission from © U.S. Energy Information Administration

The energy performance of a NZEB can be accounted for or defined in several ways. Torcellini et al. (2006) developed the following four definitions for a NZEB, each of which has its own measurement method and metrics:

- Net-Zero Site Energy: A site NZEB produces at least as much RE as it uses in a year, when accounted for at the site.
- Net-Zero Source Energy: A source NZEB produces or purchases at least as much RE as it uses in a year, when accounted for at the source.
- Net-Zero Energy Costs: In a cost NZEB, the amount of money the utility pays the building owner for the RE the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.
- Net-Zero Emissions: A net-zero emissions building produces or purchases enough emissions-free RE to offset emissions from all energy used in the building annually.

In addition to the above definitions, net-zero energy buildings can be hierarchically classified (i.e., priority levels). Pless and Torcellini (2010) categorized NZEBs into four classes from the most priority to the least priority. A building that offsets all its energy use from renewable resources available within the footprint is on top of the classification (NZEB-A). Contrary, a building that offsets its energy requirements through a combination of on-site renewables and off-site purchases is placed at the lowest class (NZEB-D). Although NZEB-A class homes are technically feasible, but not yet affordable and common for average homebuyers (NRC 2018e).