FRAMEWORK FOR SUSTAINABILITY METRIC OF THE BUILT ENVIRONMENT

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To Elie and Ella, my motivation, my inspiration, my life… To whom I dedicate all my ambitions and goals, and hope to be able to give you as much joy and love as you have given me.

To my Michella, my partner in crime, whom is the lens through which everything becomes more beautiful, more possible, and more joyable. To say I could not do this without you is an understatement,

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Sustainability of the built environment is a significant challenge facing the industry, and presents opportunities to affect changes. The absence of holistic sustainability measures has hindered their application. As a result, a sustainability performance metric (SPM) framework was formulated by employing sustainability objectives and function statements a-priori to identify the indicators that need to be captured. Projection to Latent Structures was adopted to mathematically formulate the metric. A housing prototype was used to demonstrate the application of the SPM utilizing a bespoke dataset. Results revealed that holistic metric, such as the SPM is necessary for achieving sustainable designs. A building envelope coefficient of performance metric was also developed to measure the energy efficiency of the building envelope. Results revealed the inefficiencies in the current building envelope technologies and identified missed opportunities. Furthermore, a decision-making tool was formulated and shown to be effective and necessary for design for energy efficiency.

Abstract

Sustainability of the built environment is one of the most significant challenges facing the construction industry, and presents significant opportunities to affect change. The absence of quantifiable and holistic sustainability measures for the built environment has hindered their application. As a result, a sustainability performance metric (SPM) framework was conceptually formulated by employing sustainability objectives and function statements a-priori to identify the correlated sustainability indicators that need to be captured equally, with respect to the environment, the economy, and society. Projection to Latent Structures (PLS), a latent variable method, was adopted to mathematically formulate the metric. Detached single-family housing was used to demonstrate the application of SPM. Datasets were generated using Athena Impact Estimator, EnergyPlus, Building Information Modelling (BIM), Socioeconomic Input/Output models, among others. Results revealed that a holistic metric, such as the SPM is necessary to obtain a sustainable design, where qualitative or univariate considerations may result in the contrary. A building envelope coefficient of performance (BECOP) metric based on an idealized system was also developed to measure the energy efficiency of the building envelope. Results revealed the inefficiencies in the current building envelope construction technologies and the missed opportunities for saving energy. Furthermore, a decision-making tool, which was formulated using the PLS utilities, was shown to be effective and necessary for early stages of the design for energy efficiency.

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Abbreviations and Symbols

A	*Number of components in a PCA or PLS model*
a	*Number of components for the PLS model*
ACH	*Air Changes per Hour*
ANN	*Artificial Neural Network*
ATM	*Atmospheric Pressure*
BCBC	*Building Code of British Columbia*
BE	*Building Envelope*
BECOP	*Building Envelope Coefficient of Performance*
BIM	*Building Information Modelling*
BPS	*Detailed Building Performance Simulation*
BREEAM	*Building Research Establishment Environmental Assessment Method*
c	*Weights for the output matrix*
CASBEE	*Comprehensive Assessment System for Built Environment Efficiency*
CBD	*Canadian Building Digest*
CDD	*Heating Degree Days*
CDD18	*Annual Cooling Degree Days based on 18°C*
CDD65	*Annual Cooling Degree Days based on 65°F*
CFD	*Computational Fluid Dynamics*
COP	*Coefficient of Performance*
DD	*Degree Days*
DGNB	*Deutsche Gesellschaft für Nachhaltiges Bauen eV (German: German Sustainable Building Council)*
EA	*LEED Credit Category – Energy and Atmosphere*
ECOS	*Economic Sustainability Objective Statement*
eCO_2	*Equivalent Carbon Dioxide*

EIFS	*Exterior Insulation and Finish System*
ENOS	*Environmental Sustainability Objective Statement*
EQ	*LEED Credit Category – Indoor Environmental Quality*
eq.	*Equivalent*
ERM	*Energy Renovation Measure*
EUI	*Energy Use Intensity*
FTE	*Full-Time Employee*
GDP	*Gross Domestic Product*
GHG	*Greenhouse Gas*
GWP	*Global Warming Potential*
HDD	*Heating Degree Days*
HDD18	*Annual Heating Degree Days based on 18°C*
HDD65	*Annual Heating Degree Days based on 65°F*
HH	*Human Health*
HK-Beam	*Hong Kong Building Environmental Assessment Method*
hrs	*Hours*
HRV	*Heat Recovery Ventilator*
HVAC	*Heating, Ventilation and Air Conditioning*
IN	*LEED Credit Category – Innovation*
IP	*LEED Credit Category – Integrated Process*
IUMAT	*Integrated Urban Metabolism Analysis Tool*
K	*Number of variables in the input matrix (also used as degree Kelvin)*
kg	*Kilograms*
kL	*Thousand Litres*
kWh	*Kilowatt Hours*
LCA	*Life-Cycle Assessment*
LCC	*Life-Cycle Costing*

LEED	*Leadership in Energy and Environmental Design*
LEED BD&C	*LEED for Building Design and Construction*
LT	*LEED Credit Category – Location and Transport*
M	*Number of output variables in the model*
m	*Meters*
m^2	*Squared Meters*
m^3	*Cubic Meters*
MCA	*Multiple Criteria Analysis*
MEUI	*Mechanical Energy Use Intensity*
MJ	*Megajoules*
MR	*LEED Credit Category – Materials and Resources*
Nabers	*National Australian Built Environment Rating System*
NBC	*National Building Code (of Canada)*
NECB	*National Energy Code for Buildings*
NPV	*Net Present Value*
NZE	*Net Zero Energy*
NZEB	*Net Zero Energy Building*
OE	*NBC Environment Objective*
OSC	*Off-Site Construction*
PCA	*Principal Component Analysis*
PLS	*Projection to Latent Structures or Partial Least Squares*
PM	*Particulate Matter*
PSPC	*Public Services and Procurement Canada*
PWGSC	*Public Works and Government Services Canada (currently changed to PSPC)*
Q^2	*Parameter used in Cross-Validation in PCA and PLS*
q_{BE}	*Heat Loss Through the Building Envelope*
q_{Ideal}	*Heat Loss Through the Reference (Ideal) Building Envelope*

$\dot{q}$	*Normalized Heat Transfer Rate Through Building Envelope*
QC	*Quality Control*
QCA	*Qualitative Comparative Analysis*
r	*The un-deflated w-matrix*
R^2	*Coefficient of determination*
R-value	*Absolute Thermal Resistance*
RMSEE	*Root Mean Square Error of Estimation*
RMSEP	*Root Mean Square Error of Prediction*
RP	*LEED Credit Category – Regional Priority*
RSI	*Thermal resistance*
SHGC	*Solar Heat Gain Coefficient*
SOG	*Slab on Grade*
SOS	*Social Sustainability Objective Statement*
SPE	*Standard Prediction Error*
SPM	*Sustainability Performance Metric*
SS	*LEED Credit Category – Sustainable Sites*
SSY_a	*Sum of squares of Y-Space after a-components*
SVM	*Support Vector Machines*
T	*Scores for the input matrix*
TEDI	*Thermal Energy Demand Intensity*
TEUI	*Total Energy Use Intensity*
TRACI	*Tool for the Reduction and Assessment of Chemical and other environmental Impacts*
U	*Scores for the output matrix*
U-value	*Thermal Transmittance*
USGBC	*US Green Building Council*
VIP	*Variables Important to Projection*
W	*Watts (or PLS Model Weights)*

w	*Weights for the input matrix*
*w**	*See r*
WCED	*World Commission on Environment and Development*
WE	*LEED Credit Category – Water Efficiency*
WWR	*Window-to-Wall Ratio*
X	*Input matrix*
$\hat{X}$	*Inputs used to calculate the estimated (predicted) output value*
$\bar{X}$	*Matrix of the input means*
Y	*Output matrix*
$\hat{Y}$	*Estimated (predicted) output value vector*
$\bar{Y}$	*Matrix of the output means*
$\hat{y}_m$	*Estimated (predicted) output value of indicator m*
$\bar{y}_m$	*Mean output value of indicator m*
β	*Coefficients matrix of the PLS model*

Preface

This thesis comprises of five papers, four of which have been published in or submitted to peer-reviewed journals, and one which will be submitted to a peer-reviewed journal. All papers have been co-authored. Each paper is reprinted (with permission where required) in Chapters 2 to 6 of the thesis. The following describes the contribution of G.E. Marjaba (the student) to each paper.

Chapter 2, which comprises of a reprint of the paper entitled “Sustainability and resiliency metrics for buildings – Critical review,” published in the Journal of Building and Environment Volume101 (2016) pages 116 – 125, co-authored by G.E. Marjaba (the student) and S.E. Chidiac (the supervisor), provided a complete and thorough review of the various metrics relevant to sustainability presented in literature and/or common in the mainstream industry. The documents available in literature were collected, reviewed and key conclusions synthesized by G.E. Marjaba with the guidance of S.E. Chidiac. The paper was written by G.E. Marjaba and reviewed and edited by S.E. Chidiac.

Chapter 3, which comprises of a reprint of the manuscript entitled “Sustainability Framework for Buildings via Data Analytics,” submitted to the Journal of Building and Environment, co-authored by G.E. Marjaba (the student), S.E. Chidiac (the supervisor), and A. Kubursi, presented an in-depth development of a framework for a Sustainability Performance Metric (SPM) and an associated proof of concept for single-family detached housing. G.E. Marjaba designed the data collection program and performed the data collection of all inputs and outputs with the guidance and direction of S.E. Chidiac. A. Kubursi provided the socio-economic data via a proprietary econometric Input/Output tool. The model and subsequent metric were developed, refined and tested by G.E. Marjaba under the direction and with the input of S.E. Chidiac. The paper was written by G.E. Marjaba and reviewed and edited by S.E. Chidiac and A.A. Kubursi.

Chapter 4, which comprises of a reprint of the manuscript entitled “Sustainability performance metric application to Canadian single-family housing,” submitted to the Journal of Sustainable Cities and Society, co-authored by G.E. Marjaba (the student) and S.E. Chidiac (the supervisor), provided a series of hypothetical yet realistic and practical examples of the use of the SPM to demonstrate its use, power, and importance for the design of sustainable structures. The examples in this part of the paper were designed and developed by G.E. Marjaba and S.E. Chidiac. The paper was written by G.E. Marjaba and reviewed and edited by S.E. Chidiac.

Chapter 5, which comprises of a reprint of the manuscript entitled "Building Envelope Energy Efficiency Measure," submitted to the Journal of Energy, co-authored by G.E. Marjaba (the student) and S.E. Chidiac (the supervisor), created a Building Envelope Coefficient of Performance (BECOP) metric that measures the performance of the building envelope relative to a relevant reference, allowing for meaningful interpretations and comparability with other building systems to ensure compatibility. The BECOP demonstrated the important facets of a metric and how it is necessary and how it could be used to improve performance. The metric was developed via analysis, testing and evaluation by G.E. Marjaba and S.E. Chidiac. The paper was written by G.E. Marjaba and reviewed and edited by S.E. Chidiac.

Chapter 6, which comprises of a manuscript entitled "Energy Efficiency Decision-Making Model Using Data Analytics," to be submitted to a peer-reviewed journal, co-authored by G.E. Marjaba (the student) and S.E. Chidiac (the supervisor), developed an energy and cost decision-making model that can be utilized at the early stages of the design process. This model is used as a proof of concept for the sustainability model and metric, leveraging a projection to latent structures algorithm. G.E. Marjaba designed the data collection and simulations program and performed the simulations with the guidance and input of S.E. Chidiac. The model was developed, refined and tested by G.E. Marjaba. The subsequent paper was written by G.E. Marjaba and reviewed and edited by S.E. Chidiac.

Chapter 1 – Introduction

This chapter provides a summary and sets the context for the research presented in this thesis. First, the research objectives and scope are stated. This thesis revolves around important metrics to allow practical, scientific and appropriate measures for areas of building performance that are challenging and important to measure, mainly sustainability and energy efficiency. The research hypothesizes that it is practical, scientific and necessary to measure sustainability, and using a data-analytics approach is one approach that would allow that. An alternative approach free from subjective inputs and capturing all three aspects of sustainability was not found in literature. A Sustainability Performance Metric (SPM) framework was established, and subsequently a proof of concept for detached single-family housing was developed, tested and evaluated. The methodology was also extended to a subset of sustainability, where a Building Envelope Coefficient of Performance (BECOP) metric was developed to aid in building envelope design in a holistic way, as well as a decision-making tool capable of estimating both energy consumption and costs.

The main contributions and outputs of this thesis were presented in five technical papers. One paper is published in a peer-reviewed journal, and three submitted to such a journal, and one final one to be submitted for publication. All papers are reprinted (with permission as required) in Chapters 2 to 6. A summary of each of the five papers including the main findings are presented. Each paper included recommendations for the next steps in the evolution of the outcomes, and are summarized in Chapter 7 of this thesis.

1.1 Objective of Research

In the study of sustainable systems, it is often hypothesized that meeting certain parameters would constitute a sustainable design or system [1]–[6]. In this study, as the parameters of a sustainable building design were sought, it was uncovered that the parameters that would constitute such a system are chosen relatively arbitrary from the subset or possible logical parameters, mostly based on experience and univariate considerations [7]–[10]. In a further investigation into the sustainability metrics available, none were found to be repeatable, objective, and strictly performance-based, as discussed in Chapter 2. As a result, in the search for a truly sustainable design, a scientific and practical measure or metric for sustainability was required.

The main challenge in measuring sustainability is that it requires the measurement of multiple aspects or impacts in the environmental, economic, and social impact categories. The measurements of some impacts are well understood for some impacts, and not for others. When addressing sustainability, even where the aspects that are well understood are only considered, two main issues arise: (1) impacts are often correlated (i.e. if one is changed others change as well), sometimes in an opposing direction, and that makes aggregating the results a non-trivial exercise; (2) it is impractical to calculate all of the impacts for every design, and also impractical to a larger extent to calculate them for all variations of the design in order to explore the best available solution. As a result, the objectives of these were established to address these challenges, and demonstrate the efficacy and effectiveness of the resulting solution. These objectives are articulated as follows:

Objective 1*:* *Develop a framework for a sustainability performance metric (SPM) that can be practically used in design and for decision-making on sustainable buildings design.*

Objective 2*:* *Demonstrate via a detached-single-family housing SPM prototype the application, significance, and necessity of a holistic sustainability metric.*

Objective 3*:* *Extend the logic applied to a holistic building envelope metric, and extend the methodology, in particular the suitability of data-analytic methods (Projection to Latent Structures (PLS) in particular), to an energy efficiency decision making tool for detached-single-family-housing.*

1.2 Scope of Research

To achieve the objectives stated above, three main tasks were completed:

The first task was to conduct a thorough literature review to uncover the available sustainability metrics, and subsequently assess their strengths and weaknesses. With the significant amount of research and content being developed and published in the field of sustainability, this task aimed at reviewing the literature to determine the common threads, the various commonly used metrics, and identify if any can be used as desired in this study. This included the review of the most common industry programs, LEED, BREEAM, DGNB and Green Globes, the most promising methods, Life-Cycle Assessment (LCA), and the most interesting academic methods.

The second task was to develop a framework for a sustainability performance metric formulating the design factors (inputs) and sustainability indicators (outputs) using holistic objective and function statements. The basics of the framework formed the workplan for developing and applying the prototype Sustainability Performance Metric (SPM) for single-family detached housing. The prototype was developed with the smallest possible dataset of 64 observations, and it was tested through analysing its sensitivity, analysing its boundaries, as well as several practical examples of the SPM’s use as a metric for sustainability and a decision-making tool.

The third task was to extend the methodology and logic to develop models and metrics for the building envelope energy efficiency, energy consumption, and insulation costs. By extending the logic of the need of appropriate metrics, a building envelope coefficient of performance (BECOP) metric was developed by employing a consistent reference which allowed comparison of building envelope systems’ performance to those of other systems, such as HVAC, whose performance is clearly understood via their efficiency metrics and measures. Also, by extending the methodology and leveraging a stochastic model for single-family detached housing, a decision-making tool that can be applied early in the design stage to establish cost effective passive energy efficiencies through efficient design was developed and applied.

1.3 Background

In 1963, Neil Hutcheon published CBD-48, Requirements for Exterior Walls [11], where the 11 principle requirements of a wall were defined. Conceptually, if a wall is rotated 90-degrees to one side, the wall can be considered as a floor slab, and on the other side a roof assembly (with minor adjustments to accommodate the direction of gravity). Therefore, this list of requirements can be viewed as the guideline for how to design the “perfect” building. The original list is as follows: control heat flow; control air flow; control water vapour flow; control rain penetration; control light, solar and other radiation; control noise; control fire; provide strength and rigidity; be durable; be aesthetically pleasing; and be economical.

Today, it is well understood how to account for these considerations. All the items on this list have a different priority level; i.e. fire control and strength and rigidity requirements have a higher priority than controlling rain penetration which has priority over controlling air flow and heat flow. The design principles for the items above are relatively well established, even for durability.

In 1980, Max Baker published his book called Roofs [12], where the list was slightly modified to include "provide safety in energy use." It was barely discussed. However later on in the book, energy consumption was brought up in the following context: "Recently the public has become aware that energy is in short supply, and that energy costs are continuing to rise." This was following the energy crisis in the 1970's. That crisis led to the consideration of energy-use in buildings, where insulation was added to buildings, even though at less than optimum levels.

The realization that the world's resources and supplies, especially energy supplies, were not limitless generated research and thought into this field, and sustainability started to take centre stage. This research culminated in 1987 when the World Commission on Environment and Development published "Our Common Future" [13], and sustainability in design of buildings was born [6], [14]. Subsequent to that, sustainability grew in importance to the status it holds today.

If the old masters were to come back, Hutcheon and Baker, and republish their work today, the list of requirements would likely include several considerations in the field of sustainability. Four more requirements could be added to the list, and are highlighted below (No. 12 to 15):

1. Control heat flow
2. Control air flow
3. Control water vapour flow
4. Control rain penetration
5. Control light, solar and other radiation
6. Control noise
7. Control fire
8. Provide strength and rigidity
9. Be durable
10. Be aesthetically pleasing
11. Provide safety in energy use

12. **Be resilient (by being always functional, replaceable, reusable, recyclable, etc.)**
13. **Control environmental impact**
14. **Control social impacts**
15. **Control economic impacts (also on the original list)**

In today's construction industry, fire safety, structural adequacy, and building envelop design are prescribed by codes and standards, whereas sustainability considerations and resiliency are at their infancy (the list above). They can no longer be considered as optional and the challenge is how to integrate them into current design practices.

Since the 1987 WCED report, the work on sustainability continues to mature. In the last decade or so, the subject has been gaining in importance and appears to be one field that has great potential to affect change [15]. In 1994, sustainability was defined as "the creation and responsible management of a healthy built environment based on resources efficient and ecological principles" [16]. The Brundtland Commission defines sustainability as a "condition which there is stability for both social and physical systems, achieved through meeting the needs of the present without compromising the ability of future generations to meet their own needs" [13].

As a result, to design a building adequately, where sustainability considerations are measured, quantified and designed for, similar to the other 11 considerations on the list, a sustainability metric has to be utilized. The metric has to be scientific, performance-based, and practical to use, which is what motivated the work performed and described in this thesis.

1.4 Summary of Papers

In this section, a brief summary of each of the papers comprising this thesis provides insight into the objectives and findings of each paper.

Chapter 2 – Sustainability and resiliency metrics for buildings – Critical review

Published in Journal of Building and Environment (March 2016)

The review conducted in this paper was motivated by the need for metrics to measure the sustainability performance of traditional versus innovative construction methods, namely off-site construction (OSC). Current metrics for sustainability and resiliency for buildings are reviewed to determine their state of development and application. The review uncovered several potential metrics to measure sustainability performance, or portions of sustainability. Life cycle assessment (LCA) methods were found to be considered currently as the state-of-the-art in addressing sustainability performance, focusing mostly on the environmental impacts, however it faces significant challenges. Other voluntary industry programs, such as LEED, BREEAM and DGNB are found to be useful at meeting their purpose, however they fail at measuring sustainability performance in all its aspects in a repeatable, reproducible and adequate reflection of true building performance. Other sustainability metrics for industrial processes and other industries were found to be more advanced in comparison to those used for buildings. Finally, the review uncovered another challenge in assessing the resiliency for buildings, particularly in-tandem with sustainability. As a result, the need for a sustainability metric for buildings that addresses those challenges was exposed and its importance highlighted.

Chapter 3 – Sustainability framework for buildings via data analytics

Submitted to the Journal of Building and Environment (October 2019)

The challenge of resolving how to manage the complex interactions of sustainability which encompasses the three prongs, social, economic and ecological impacts within a scientific metric is addressed. This is further challenged by the fact that sustainability indicators are often influenced by a multitude of correlated factors, where intuition and qualitative analyses where shown not be adequate or productive. As a result, in this paper a Sustainability Performance Metric (SPM) framework was presented based on a logical formulation based on clear objective and function statements applicable to a wide range of fields. Subsequently, by leveraging a PLS algorithm and subsequent model to underpin the SPM, the framework was applied and tested via a prototype for single-family detached housing. A fully-saturated dataset of 64-observations was used to demonstrate the possibilities of scientifically and practically measuring sustainability. Eighteen (18) sustainability indicators or impacts are measured spanning all three areas of sustainability. The SPM ensured that the environmental, social and economic categories had equal weight and importance. The SPM provides a positive number that the designer should aim to minimize, where current high-performing housing would be expected to have an SPM around 0.33, and poorly performing housing an SPM of 1.67. This paper demonstrated the need for an SPM where without a holistic metric, unsustainable designs may result, as well as the efficacy and effectiveness of the SPM were shown. The framework for developing the SPM for any type or types of buildings is only contingent upon being able to generate an appropriate dataset.

Chapter 4 – Sustainability performance metric application to Canadian single-family housing

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The paper presents the practical use of the SPM in several case studies. First, both SPM and LEED are examined to determine the interaction between the two. In a design case study, using a typical trial and error exercise to select an option to achieve a more sustainable design, the SPM and LEED were calculated for five options. The SPM and LEED were shown to follow different trends. It was also shown than the univariate consideration of factors may in-fact result in unsustainable design decisions being inadvertently made. The second case study demonstrates an alternative to using the iterative trial and error approach, where the designer can leverage the linear nature of the PLS-engine underpinning the SPM to mathematically find the global optimal solution for a specific set of design constraints. The optimal design highlighted the significant room for improvement present. The SPM’s power as practical and scientific metric that is free of subjective evaluations is also demonstrated. It was also shown that a metric such as the SPM would result in more economic designs, more environmentally friendly designs, and more socially conscious designs compared to only using experience of univariate analysis of sustainability.

Chapter 5 - Building Envelope Energy Efficiency Measure

Submitted to the Journal of Energy (October 2019)

In this paper, a Building Envelope Coefficient of Performance (BECOP) as an efficiency measurement metric is presented after an analysis on current building envelope measures and metrics, including a review of Canadian building code requirements. The BECOP focuses on its practicality and interpretability, particularly for building envelope design decisions which are unpractical to update later in the design and construction process. It was found that the metric is practical to use by owners and regulators as well as designers. The BECOP metric is independent of building type and calculation methodology. Three case studies are presented in this paper for single-family detached houses. The case studies presented in hypothetical and realistic situations for the design of a new house, another for the design of a retrofit for an existing house, and finally design of regulation or for regulatory compliance. The BECOP was shown to be intuitive in its interpretations, captures the building envelope performance as a system, and captures when opportunities to improve are leveraged or not. This leads to making informed decisions in the design of new buildings, design of retrofit programs, as well as possibly the design of regulations, standards, and programs. The BECOP metric demonstrated the power, importance and use of a well-designed metric, concepts which were used in the development of the sustainability metric.

Chapter 6 – Energy efficiency decision-making model using data analytics

To be submitted to a peer-reviewed journal

In this paper, a model estimating energy consumption and insulation cost (using an analogue) was developed and presented for single-family detached housing using a stochastic 13-input model as a framework for developing practical decision-making tools and models. The outputs used in the decision-making model were annual energy consumption and insulation cost analogue. The costs estimation provides an opportunity to consider cost versus benefit. The resulting model was sufficiently practical to be programmed into a spreadsheet as to provide instantaneous and simultaneous estimation of annual energy consumption and cost analogue. The use of this tool/model was demonstrated in design of new and retrofit projects, design and implementation of regulation, labelling programs and incentive programs examples. The final results demonstrated the adequacy and need for such models, and the potential to affect change in the mainstream industry that is both cost- and energy-conscious.

Chapter 2 – Sustainability and resiliency metrics for buildings – Critical review

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Abstract

The driving forces for change in the construction and building industry are several, not least of which are health and environmental awareness combined with the innate urge to improve living conditions and standards under economic constraints. Based on in-depth observation of the current practices, improved practices, market conditions, and driving forces, it is postulated that the next logical advancement in building construction technology is manufactured-modular-prefabricated-off-site construction, referred to as off-site construction (OSC). Accordingly, current metrics for sustainability and resiliency for buildings are reviewed for determining their state of development and application. The review revealed that a variety of metrics exist to prove any sustainability claims, or portion thereof. Of all the metrics, life cycle assessment (LCA) is currently the state-of-the-art in quantifying parts of sustainability, namely the environmental impacts, however it faces significant challenges. Certification systems, such as LEED, BREEAM and DGNB are found to be useful and successful at meeting their purpose, however they fail to address all of sustainability's requirements. Moreover, these certification systems have yet to produce metrics that are repeatable, reproducible and true reflection of the building performance. Sustainability metrics for industrial processes and other industries were reviewed and found to be more developed in comparison to those used for buildings including methods such as the Canberra and Mahalanobis distance been employed to aggregate the various sustainability factors. The review also revealed that there are no metrics for assessing the resiliency for buildings, particularly in-tandem with sustainability. Of relevance to OSC systems is the certification systems' inability to adequately account for innovative and new construction techniques and material. Although OSC systems have shown potential for being a sustainable construction system for residential, commercial and industrial buildings, the review revealed that the potential is missed in the absence of a true sustainability and resiliency metrics for building systems.

1. Introduction

Reviewing this century's development of the most prized possession of man – buildings, homes and structures, mainly the methods of building them, the advancement is relatively less obvious and inspired than the advancement in most other technological sectors. One could speculate on the economic, social, psychological, etc. reasons for this slower rate of development. However, it could be summarized that until the late seventies or eighties, decisions were based on the lowest initial cost and the belief that Earth's resources are limitless. Subsequently, the advancements were directed towards improving material properties to build more cost efficiently. Today's construction philosophy has shifted demanding change of how things are built.

The driving forces for change are several, not least of which are health and environmental awareness combined with the innate urge to improve living conditions and standards under economic constraints. Based on in-depth observation of the current practices, improved practices, market conditions, and driving forces, it is postulated that the next logical advancement in building construction technology is manufactured/modular/prefabricated/offsite construction, referred to as off-site construction (OSC), of structures. This study provides a review of current metrics for sustainability and resiliency as a mean to establish the necessary and sufficient conditions to evaluate the trueness of the postulation.

The claim that OSC is a more sustainable construction technique should result in an increased uptake in this sector, however the uptake is slow and/or stalled in some situation. Therefore, this study will first examine the claim of improved sustainability and resiliency, which requires a framework in order to measure and evaluate this performance aspect. Accordingly, this review will focus on 3 themes which form the objectives of this paper: 1) Sustainability and resiliency of buildings; 2) Sustainability and resiliency metrics; and 3) Off-site construction and sustainability and resiliency of off-site construction. The 1st theme aims to uncover the current understanding of sustainability and resiliency; specifically, what performance areas are considered when sustainability and/or resiliency are evaluated. The scope is limited to buildings and similar structures. The objective of the 2nd theme is to identify existing sustainability and resiliency metrics put forward in the technical literature with the aim to establish their strengths and shortcomings. The scientific literature with respect to OSC and sustainability and resiliency are reviewed as part of the 3rd theme.

Research in the area of sustainability has produced a significant amount of knowledge that is presented in the literature. Although being well-defined from an academic point of view, sustainability is a term used liberally and loosely in layman's literature and academia alike. For

OSC, research has been more precise in comparison to sustainability, and includes many claims of OSC being a more sustainable construction method compared to traditional construction. These claims are usually supported by addressing one or several aspects of sustainability, e.g. worker safety, waste reduction, speed of construction, life-cycle assessments (LCA), etc., however not combining all aspects. The objective of this paper is to review the state-of-knowledge pertaining to sustainability and resiliency metrics for evaluating buildings, OSC, and the maturity of these metrics for adequately evaluating the sustainability and resiliency of different types of construction including OSC.

2. Sustainability and resiliency in buildings

A literature review of relevant articles on sustainability and resiliency of buildings published between 1987 and 2015 revealed major commonalities; 1) common understanding of what sustainability refers to and its origins, 2) importance of construction activities and subsequent buildings and structures to the overall sustainable performance of human activities, and 3) definitive need to measure, evaluate/analyse and report sustainability and resiliency performance in order to address sustainability scientifically and apply engineering principles to it.

The origin of sustainability is commonly attributed to the 1987 Report of the World Commission on Environment and Development (WCED) entitled “Our Common Future” and referred to as the Brundtland Commission report [15]. Accordingly, sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [10]. Several other definitions and refinements are reported in several sources. In 1994, sustainability was defined as “the creation and responsible management of a healthy built environment base on resources efficient and ecological principles” [11]. The Brundtland Commission further refines the definition of sustainability as a “condition which there is stability for both social and physical systems, achieved through meeting the needs of the present without compromising the ability of future generations to meet their own needs” [11]. The Brundtland Commission definition is the most widely accepted for sustainable construction [46]. Another interesting and broad definition is: “building design and construction using methods and materials that are resource efficient and that will not compromise the health of the environment or the associated health and well-being of the building's occupants, construction workers, the general public, or future generations” [36]. There are many definitions reported for sustainability, however the ones quoted are found adequate for the study. Of more significance was the general agreement of the design community that sustainability has to consider three major categories: environmental, social and economic impacts [4,46]. In practice, there are deviations from considering all three aspects of sustainability due to the difficulty of measuring economic and social impacts within the current engineering and scientific methods. For example, environmental impacts are stated as the focus of sustainability studies, however social and economic impacts are usually declared as being important without being directly considered. Therefore, the environmental requirements can be termed essential conditions that are imposed explicitly on the design whereas the social and economic requirements as natural conditions that are hopefully satisfied through the design.

Having stated the definition of sustainability and its three prongs environmental, social and economic impacts, there is significant confusion and looseness in the use of word and concepts of “sustainability,” “green,” etc., in the scientific community, industrial community and political communities alike. This inaccurate use of these concepts and terms was important to consider as part of this literature review and subsequent study.

The second major common theme that was seen in the review is the importance of construction activities to the economy, the society, and the environment. There is an absolute need to improve sustainability performance of buildings, including their construction. There are many statistics that support these claims throughout the reviewed research. To further illustrate, consider the following brief discussion.

Since the 1987 WCED report, the work on sustainability continues to mature. In the last decade or so, the subject has been gaining importance and appears to be one field that has great potential to affect change [4]. Sustainability in construction as reported by the World Watch Institute show that 55% of the wood resources are used for construction, 40% of the materials and energy produced in the world are used by buildings, and 30% of buildings expose occupants to stale or mould- and chemical-laden air [58]. Similarly, in Canada, PWGSC reported that about 7 million of the 20 million tonnes of solid waste sent to landfills are from the construction and renovation activities [55]. Subsequently, “with the landfills operating close to maximum capacity, the costs associated with discarding wastes has risen by a factor of 5 over the last 30 years” [55].

There is ample research indicating that majority of the impact of a building is during its occupancy phase. However, the construction phase in itself has a measurable and significant impact. Also, in many technical areas, the decisions and construction methods will impact the performance during the occupancy and demolition or reuse phase, further illustrating the importance of the construction activities to all aspects of sustainability.

The third and final common theme that emerges from the literature review is that there is a need to measure and report sustainability performance of construction activities and subsequent buildings. The need to measure is required to allow designers to confirm, validate and quantify sustainable design improvements, as well as to help regulators and politicians make informed decisions on policy that actually improve sustainable performance. Due to this need, measurement systems are devised and packaged in various ways, the most popular of which are certification systems such as LEED, BREEAM, DGNB, etc. The literature on this topic is further discussed in the following sections of this paper. However, under this first theme of “Sustainability and Resiliency in Buildings,” the literature reveals that currently there is no robust metric that is repeatable and measures actual performance [54].

While reviewing the literature, a pivotal observation was noted in some key references. In policy and governmental strategic documents, namely the “Strategy for Sustainable Construction” document [27], every technical area of sustainability was considered with a requirement or at least a consideration for measurement and reporting of sustainable performance. This trend continues and evolves in more recent documents.

This need for measurement and reporting techniques is echoed in “How to make housing sustainable? The Dutch experience” [54], which is another interesting reference. It argues that the term sustainability is surrounded by vagueness, is overused and is not accurately defined particularly in policies and non-academic literature where the methods of measuring sustainability are not well defined, and that there is an absolute need to measure it. Moreover, the author demands that the focus be only on environmental aspects in order to make the concept of sustainability more workable, but then claims that economic and social aspects are also very important and cannot be ignored. The main recommendations of that review relevant for this research are" [54]:

- The need for empirical measurements.
- Environmental qualities must be combined with essential and "familiar qualities, such as addressing the demand-driven market, flexibility, affordability, and technical reliability. If ecological quality were to subsume these other qualities, disappointment will surely result." This is consistent with the need to consider social and economic impacts.
- Continuous review of performance and dissemination of results and new knowledge.
- Don't fall into the micro-scale improvements that could have a negative impact on the macro-scale.

Priemus [54] concluded that sustainable housing is so diluted as defined in many policy documents and academic publications that it lost its objective and became equivalent to good housing. He added that there are no measurable distinctions between the sustainability of housing development, management, use, and renovation/restructuring. Moreover, there are no suggestion of a standard for measuring sustainability or environmental impacts.

As for resiliency, according to Merriam-Webster online dictionary, it is defined as "ability to recover from or adjust easily to misfortune or change", where misfortune is also a defined term, "an unlucky condition or event" [44]. Putting the two definitions together for buildings, a building resilience is a measure of the building's ability to recover from or adjust easily to an unlucky condition, event, or change. These conditions could be severe environmental conditions such as buildings in coastal areas exposed to corrosive salt and moisture laden air. These events could be natural disasters such as earthquakes, tornados and tsunamis, or man-made disasters such as explosions and fire. Finally, the change could be a change in building use.

In the reviewed literature, resilience is defined as "resistance to natural disasters" [63] where it is sometimes extended beyond natural disasters to include "changing conditions" and "emergencies" [31]. However, it is still limited to sudden and unexpected events although most natural disasters and emergencies are expected but their timing, magnitudes and durations are not known. As per this definition, "unlucky conditions" and "change" are not addressed within the concept of resilience; they are dealt with under the concepts of durability and flexibility. Durability is defined in BS 7543-1992 as “ability of a building and its parts to perform its required function over a period of time and under the influence of agents” [39].

For a complete discussion on resilience of buildings, durability and flexibility have to be included. However, since the concept is fairly new, resilience metrics are in their infancy, and metrics, particularly certification programs are being developed where the focus is narrowed down to natural disasters, namely earthquakes [63]. There is also work conducted on including other natural disasters and emergencies [31], however durability and flexibility are treated separately. Durability is the most mature of the areas above where the concepts of service-life, reliability analysis, etc. are developed [12,39,61]. Furthermore, Matthews et al. [43] reported that resilient performance is not adequately featured in sustainability metrics and is considered a weakness in current metrics. In summary, the sought-after metrics need to include sustainability and resiliency for all three phases of the buildings' life cycle as illustrated in Fig. 1.

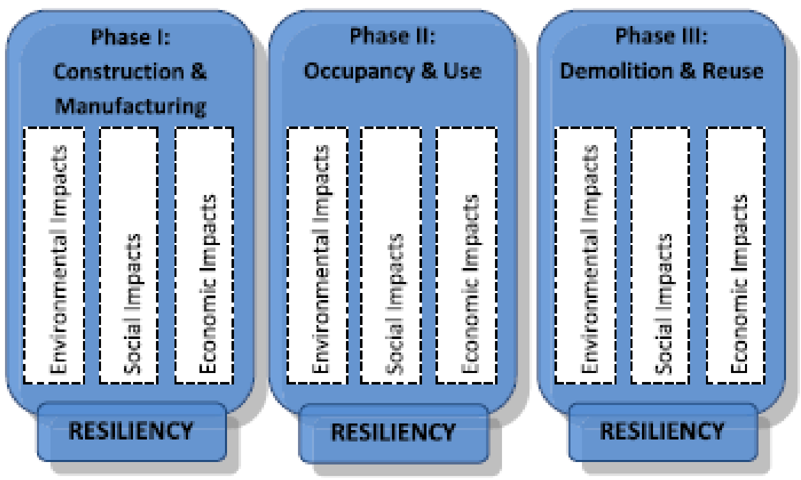

Figure 1. Schematic illustration of the relationship between sustainability, life cycle phases and resiliency.

3. Sustainability and resiliency metrics

Review of peer reviewed articles, codes, and industry publications published between 1987 and 2015 revealed three major commonalities; 1) in order to evaluate sustainability or an aspect of sustainability, a metric is always specified and usually stated in the article title, 2) there are many metrics used in the literature, however the life cycle assessment (LCA) method is by far the most popular and comprehensive, and 3) even though certification systems such as LEED are very useful and continue to evolve, they are rarely used in academic literature as a means to validate, prove or measure sustainability performance and behaviour.

While reviewing the literature, it was observed that most if not all the research on sustainability pertaining to a specific product, system, or even policy, the method for measuring performance was always prominent. Examples include LCA for a new material [1,9,32,67], energy consumption of a new building [1], emissions from a specific process and optimization of CO_2 emissions for a certain product [23,40,68,71], etc. The metrics specified here are LCA, emissions usually tonnes of CO_2 and other emissions, where optimization process have also been used to minimize emissions or other properties. This indicates that no claim can be validated without having a metric. Subsequently, improvements and recommendations can be made, design guidelines can be used, and evaluation frameworks can be proposed.

The second commonality stems from the first one, i.e., metric is needed to make and validate any claim of sustainability regardless of the measure or performance. Of all the methods reported, LCA, which is regarded as a true metric, is found to be the most used with the ability to capture one or more measure. Moreover, LCA method framework is set by ISO 14040-series of standards [30]. The following observations were noted for the LCA method:

a. LCA as described by ISO 14040 is designed to only address environmental impacts [30]. The framework laid out by ISO could potentially be expanded and modified to address economic impacts (e.g. life-cycle cost calculations) and social impacts (criteria have yet to be defined). Accordingly, LCA in the reviewed literature is found to only address environmental impacts.
b. LCA of material, component or system requires extensive amounts of data. Accordingly, LCA studies are feasible when conducted as part of a research study, or by the manufacturer or supplier of a particular product. LCA of whole-building is found to require tremendous amount of data that makes the method impractical to be considered for design or decision-making processes.
c. LCA studies are complicated, time consuming, and require experts.

d. LCA is not necessarily repeatable. Different qualified professionals could potentially get different LCA results due to the sensitivity of the method to input data variations and embedded assumptions.

The third and final common theme is certification systems and codes. They are discussed extensively in the literature especially LEED and BREEAM. Certification systems are useful, however there are important gaps and loopholes that are a result of the need to make these systems practical to increase their adoption, and subsequently their impact and reach. They are being continuously improved to close these gaps [8,66].

Codes, such as the National Energy Code for Buildings of Canada [47] also have an impact on sustainability. However, as the name implies, these codes usually address only a fraction of sustainability, and their scope and mandate are not as far reaching as the certification systems or other metrics. They are however important to consider while conducting this research as they can mandate new trends.

Regardless of the importance and usefulness of the certification systems and codes, they are not used in the literature to measure sustainability performance, to validate sustainability claims, or to make suggestions to improve that aspect of performance. This is due to the fact that they are not true metrics that are repeatable and reflect true performance [65]. This aspect is further discussed and described as part of the review of these methods.

3.1. Life cycle assessment

LCA was developed in the early 1960's in an effort to quantify the environmental impact of various packaging options at the Coca Cola factory [28]. It has now been developed and standardized into an analytical framework in the ISO 14040-series of standards. LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [30]. It is a flexible tool that allows for measurement of specific impacts throughout the life cycle of a product, component, material, system, processes, etc. The flexibility allows for varied identifications of start- and end-stages to be considered (scope), impact categories (criteria) and other measurement aspects. This is somewhat controlled through the ISO

14040 standard that sets the framework for conducting these types of assessments. The standard is aimed at managing environmental impacts, and does not address social and economic impacts, however the same principles of the standard may be used [30]. LCA tool requires a significant amount of data that may or may not be readily available, which makes the application of this method to complex systems, such as buildings, prohibitive in most cases.

Significant LCA's and research have been conducted for building components which have the most significant environmental impact [51]. This research is limited to components of buildings or simple building systems. On the other hand, there is little research done, besides case-specific studies, for wide-spread use of whole building life cycle assessment. The reason is the impracticality in applying LCA for whole building life cycle analysis [35,42,54,56,60].

LCA studies conducted on the whole building life cycle have confirmed that the most significant environmental impact of a building is during its occupancy phase. Scheuer et al. [59] completed a comprehensive LCA study of a 6-storey, 7300 m^2 mixed-use building at a university campus to confirm that fact, however the only area where impacts were comparable are in the areas of waste production where construction and material production account for approximately 28% of the impact compared to 65% generated during the occupancy phase. Furthermore, Quale et al. [56] found that in general, construction phase consumes 2% of energy and causes 1% of green-house gas emissions, 7% of carbon monoxide emissions, 8% of nitrogen oxide emissions and 8% of particulate matter emissions. On the other hand, Ochoa et al. [49] found that in the US, the construction phase in general is found to contribute 57% of toxic air emissions and 51% of hazardous waste generations. Similar results are found by others [32] for other impact categories.

Complete building LCA is found impractical. When examining the results of Quale et al. [56], one finds that significant assumptions are needed to simplify the structures as a-priori to carry an LCA. These assumptions impact the decision making and evaluation process, and more importantly, they can compromise comparative analysis of alternatives, thus rendering LCA non-practical and nonreliable for decision making. Similar and other challenges were revealed by Lotteau et al. [41] when reviewing LCA studies conducted on a neighbourhood scale. LCA's are dependent on impact categories which could in theory span environmental, economic, and social aspects, however, the data is not always available particularly for social impacts. Furthermore, using LCA for economic and social impacts falls outside the framework of ISO 14040.

3.2. LEED, BREEAM, and DGNB

Sustainability performance needs to be measured, quantified, and/or assessed in order to determine which construction system, technique or material perform from a sustainability point of view. The need for a sustainability performance metric and publicity tools gave rise to the development of certification rating systems. These rating systems are not necessarily sustainability metrics or rating systems since they do not all include the three prongs of sustainability, and/or all three aspects are not valued equally. The most popular rating systems focus mostly on the environmental impacts. Some overlap exists between all aspects, and economics usually find their way into designs. Therefore, it can be argued that these systems provide a measure of sustainability even though their focus is on environmental impacts.

Building rating systems are tools developed to aid in evaluating building sustainability. A large number of these tools have been developed aiming at providing a comprehensive metric to evaluate and compare the impact the components and operations of a building have on human well-being and the natural environment [22]. Some examples of such tools are CASBEE in Japan, Nabers in Australia, HK-Beam in Hong Kong [22], BREEAM in the UK and DGNB in Germany. The most popular of all, the USGBC-sponsored Leadership in Energy and Environmental Design (LEED) Green Building Program is widely considered as the largest program in the United States for measurement, verification and certification of green buildings [23]. They are extremely similar from a metric for sustainability point of view where one only gets to the nuances and minute differences in methods to catch a glimpse of major differences in philosophy, even though credits, weighting systems, categories, etc. may be significantly different. Most of these tools do not address all three aspects of sustainability equally. Most emphasis is being placed on environmental impacts, ignoring the importance of the social and economic impacts [15]. These tools have played an important role in commercialization and adoption of designing buildings for sustainability. Three systems, namely LEED, BREEAM, and DGNB were critically reviewed and a brief summary is given below. Table 1 shows a comparative analysis of the three systems with respect to their treatment of all three aspects of sustainability. Of significance is that only DGNB places equal weight on all three aspects of sustainability whereas the other two place most weight on the environmental aspect.

3.2.1. LEED

The LEED certification system is a credit-based system which provides credits for a particular building design. The credits are given for eight (8) different categories as documented in version 4 (v4) of Building Design and Construction for New Construction [66]. Each category has different weight with the aim to give more credits to aspects with a higher positive impact. The weighting is determined based on the U.S. Environmental Protection Agency's TRACI and a research exercise conducted by the National Institute of Standards and Technology [66]. LEED, like the other certification tools, provides a practical package to apply research findings.

There are different requirements for different occupancy and use types. However, it does not differentiate the buildings by construction method. LEED can be applied to innovative construction methods and earn additional credits within the system. Having said that, many of the fundamental attributes of innovative systems are not captured by LEED. Resiliency and quality of construction are two attributes that could be missed for innovative systems. For example, consider an OSC system designed to allow efficient repair such as a modular system that permits the replacement of any module without demolition or damage to another part of the structure. This attribute would be significant for buildings damaged by events such as an earthquake, blast damage, or change in use. The improved resiliency performance of such a system is not captured. It should be noted that such a system may receive some innovation credits, however it is neither adequate nor an appropriate measure of the system performance. Another example would be a hypothetical system that provides better quality which “should” translate into longer durability and an increase in potential for reuse. This improved sustainability and resiliency performance would not be captured and measured. Many more examples exist for innovative systems that the current performance attributes could miss.

Finally, although LEED attempts to address all aspects of sustainability, it is generally described as a green building certification rather than a sustainable building certification. Therefore, it puts more emphasis and weight on the environmental aspects of sustainability.

Table 1. Comparative look at the treatment of various aspects of sustainability by subsections of LEED, BREEAM and DGNB.

	LEED [66] (110 credits)	BREEAM [8] (1) (143 to 151 credits)	DGNB [18] (2) (percentage based)
Procedural	Integrative Process ≈ 1 credit Innovation ≈ 6 credits Total: 7 credits ≈ 6.5%	Management ≈ 12-14 credits Innovation ≈10 credits Total: 22 to 24 credits ≈ 16%	Process Quality ≈ 10% Total: ≈ 10%
Environmental	Location and Transportation ≈ 14 credits Sustainable Sites ≈ 9 credits Water Efficiency ≈ 11 credits Energy and Atmosphere ≈ 33 credits Material and Resources ≈ 12 credits Total: 79 credits ≈ 72%	Management ≈ 6 credits Energy ≈ 28 credits Transport ≈ 11-14 credits Water ≈ 9 credits Materials ≈ 10 credits Waste ≈ 6-7 credits Land use and ecology ≈ 12 credits Pollution ≈ 17 credits Total: 99 to 104 credits ≈ 69%	Environmental Quality ≈ 23% Technical Quality ≈ 8% Total: ≈ 31%
Economic	Regional Priority ≈ 4 credits Total: 4 credits ≈ 3.5%	Management ≈ 3 credits Materials ≈ 1 credit Total: 4 credits ≈ 2.5%	Economic Quality ≈ 22% Technical Quality ≈ 6% Total: ≈ 28%
Social	Location and Transportation ≈ 2 credits Sustainable Sites ≈ 1 credit Material and Resources ≈ 1 credit Indoor Environmental Quality ≈ 16 credits Total: 20 credits ≈ 18%	Management ≈ 1 credit Health and Wellbeing ≈ 16-18 credits Pollution ≈ 1 credit Total: 17 to 19 credits ≈ 12.5%	Sociocultural and Functional Quality ≈ 23% Technical Quality ≈ 8% Total: ≈ 31%

Notes to Table:

(1) Section weighting not included in the percentage calculations.

(2) DGNB New office and administrative buildings, Version 2012.

3.2.2. BREEAM

BREEAM rating system is a credit-based system similar to LEED. However, it claims to be a sustainability best practice [8] rather than a green building best practice. It attempts to address ten (10) different “environmental sections of sustainability,” with various credits and weights.

BREEAM includes more flexibility: (a) for local applications it allows for the application of local codes and best practices and (b) for international application it incorporates enough flexibility for customization for application globally. It allows for geographic flexibility, but does not lend itself for the evaluation of sustainable performance of innovative systems.

From another perspective, BREEAM includes several credits that capture the sustainable performance of the construction process, however it does fall short with addressing long-term durability, resiliency, and improved quality through innovative systems (exceptions may exist). Even though BREEAM addresses social and economic impacts to a greater extent than LEED, it predominantly measures environmental impacts.

The cases presented for the short comings of LEED being used as a sustainability metric apply for BREEAM as well. Another common issue with using LEED or BREEAM as sustainability metrics that was not previously mentioned is the prescriptive paths. Prescriptive paths provide credits for following a prescribed procedure or method, or using a prescribed product, without actual measurement of the performance of that procedure or product for a particular situation. Therefore, the prescriptive paths do not measure or reflect actual performance, rendering BREEAM (and LEED) not adequate for use as a sustainability metric that measure, reflect or quantify performance.

3.2.3. DGNB

DGNB is a recent development in the field of sustainability rating systems; however, it is the most complete since it addresses all three aspects of sustainability (see Table 1) in a matrix scoring system described in Figure 2. The DGNB is more flexible and comprehensive which makes it more complicated as well as requiring a significant amount of technical data [15]. The lack of data, practicality and access to the DGNB rating system make this system challenging to use, review and study.

To summarize most of the certification systems can be generally described as such: (1) A number of variables deemed important to sustainability are selected. (2) Provide a scoring scale that is measured relative to minimum acceptable standards and best practices, measured relative to a benchmark, or subjectively assigned a score by an “expert.” (3) Provide a weighted average and subsequently a certification level.

The processes within the certification systems package research in sustainability, market conditions, available products, construction practices, and innovation into a practical number or unit. These units aim at being easy to apply and encourage design for sustainability. They also create the necessary market conditions for adoption and change, and this is where the value of these systems resides.

All three systems (and others such as Green Globes, Casbee, etc.) have raised the awareness of sustainability and environmental concerns and are applied accordingly to encourage sustainability practices. The commercial success of these systems is a clear indication that these systems have achieved their goals, and their continued evolution aims at capturing more areas of sustainability and closing loopholes. Application of these certification systems may have led in some cases (not all) to improved environmental performance [64]. Having said that, for the purposes of being a sustainability metric, three criteria need to be met: (1) ability of the system to quantitatively measure performance, (2) ability of the system to be repeatable, and (3) quantitatively measure the performance for all areas of sustainability: environmental, economic and social aspects. These types of certification systems do not sufficiently meet either criterion.

Figure 2. DGNB parameters and structure [17].

3.3. Other sustainability and resiliency metrics

The review addresses other metrics reported in the literature to either gauge the sustainability of an industry or industrial process, and/or to provide a methodology for aggregating the contribution of multiple sustainability indicators. Although these topics are somewhat outside the scope of the paper, their review provides an insight into the state-of-knowledge and application of sustainability metrics to engineering problems. For example, Dewulf & Van Langenhove [16] used the concept of industrial ecology referred to as industrial metabolism to evaluate the environmental impact of products and processes. They accounted for all mass and energy transfers throughout the entire life cycle by employing exergy as the primary factor and assessed sustainability by tracking resource renewability, toxicity, material reuse, recoverability at end of use, and efficiency. They considered toxicity a measure of social impact and the rest as environmental impacts. The authors proposed this concept for comparative analyses and therefore no attempt was made to combine the impact of all five categories. This concept is found to be rational when evaluating the true life cycle impacts of a system. Mostafavi et al. [45] adopted the same principle along with an Integrated Urban Metabolism Analysis Tool (IUMAT) to evaluate the environmental impact of urban design alternatives. The tool provided an assessment of the proposed development on the environment and modelled the impacts of social and economic factors on the environment. The tool did not consider the impact of the development on society and the economy.

Fagan et al. [21] discussed the need for sustainability metrics to evaluate urban water systems, and used first principles to assess environmental impact and economic feasibility of alternate solutions. They argued that existing metrics do not have the resolution required to pick up dynamic variabilities, and therefore they used dynamic material and energy balances, thermodynamics and kinetics, along with LCA process to create a dynamic modelling framework to generate the required measurements for water, wastewater, energy consumed, etc. They subsequently applied this framework to a case study and were able to make some interesting conclusions about the sources of greenhouse gas emissions from the water system, options for a net decrease in emissions, etc. Hajkowicz & Collins [26] utilized a sustainability metric based on multiple criteria analysis (MCA) to develop a decision tool for investors in Australian agricultural applications. The method included weighting criteria, transformation techniques, and aggregation techniques to reach the desired goals. Optimization techniques were also utilized to drive policy developments. The strengths of this method are its simplicity and scientific approach, however it does not address aspects beyond the environmental impacts, uses weighting criteria developed by expert surveys, and ignores the specifics when adding the separate environmental impacts.

Patil et al. [53] described the requirements for target cascading of environmental impacts in the automotive and manufacturing sector. This shows that an evaluation of environmental impacts on the final product does not allow for decisions to be made at a stage where change is feasible. The authors proposed a method to “cascade” or decompose the environmental performance target of the final product into targets assigned to the subsystems. Conceptually, it is comparable to assigning performance targets to a building's subsystems such HVAC, structural, cladding, etc. while accounting for the whole building target. Unfortunately, the authors stopped short and did not present actual targets and metrics.

Sikdar et al. [62] proposed applying pairwise comparisons of various alternatives using distance metrics such as square roots of the sum of the squares and Euclidean distance to collapse or aggregate a number of indicators into one value, in this case a distance. They found that in order to handle all types of indicators - zero, infinite, negative, etc. - data transformations were needed.

Several case studies were presented to illustrate the method in the automotive industry. Brandi et al. [7] put forward another method to aggregate different indicators spanning the social, economic and environmental aspects using the Canberra distance method. Comparing the Canberra distance aggregation method to the one proposed by Sikdar et al. [62]; the authors found that the transformation creates a bias by injecting a "value judgment" into the indicators. They concluded that the Canberra distance manages indicators of different units, is scale invariant, and can handle negative and zero values. Subsequently, dos Santos & Brandi [19] investigated the use of Euclidean, Mahalanobis, Canberra, and z-score-normalized Canberra distances to aggregate the sustainability indicators for a biodiesel supply chain and found that Canberra distance and Mahalanobis distance are the most adequate for this particular application.

El Shenawy & Zmeureanu [20] proposed an exergy-based sustainability index to aggregate the environmental sustainability indicators for buildings by using a MCA, LCA, and exergy calculations. Five buildings located in Canada with different age, use and location were used for illustration. They reported that the exergy method and exergy index provide a wealth of embedded information about the environmental impacts of energy retrofit measures throughout the life cycle of the buildings. Of interest was the realization that energy retrofits or energy efficient new construction such as net-zero buildings experience a reduction in environmental benefits when the primary energy embodied within the improved construction material is accounted for.

This review reveals that despite the complexities of the subject, significant advances have been made towards developing sustainability metrics for industrial processes and for aggregating the various factors. Moreover, the review exposes the loose usage of the term "sustainability" in other industries where the focus is primarily limited to environmental impacts, and resiliency is not quantified or measured as part of any sustainability metrics.

4. Off-site construction and sustainability and resiliency of off-site construction

Off-site construction (OSC) is not a new innovation in itself, since it has been recorded as early as 1851, and some even argue that it dates back to ancient Egypt [33]. The modern form of OSC which takes advantage of technological advances in manufacturing, building information modelling, among others is currently being globally recognized as the future of the construction industry and its uptake is on the rise [50,57]. OSC uptake rate appears to be slower than anticipated due to logistic barriers. Regardless of these barriers, many companies have implemented the transfer to OSC, but the industry as a whole is yet to capitalize [50]. In Australia, Blismas et al. [6] report that OSC would provide many benefits to the construction industry, and the players or sub-industries that are able to properly utilize OSC stand to gain a significant advantage in the marketplace. The barriers reported are mostly logistical in nature where the strategic shift to OSC needs to overcome supply chain issues, training challenges, perception challenges, etc. [6]. Khalfan & Maqsood [33] also concluded in their study that the construction industry in China, Hong Kong and Australia need to increase adoption of OSC systems since the barriers are not related to the product itself, but to logistical barriers that have been resolved by other industries. Moreover, there is a perceived and/or real additional cost for OSC as opposed to traditional construction which is hindering the adoption of OSC [33]. This observation is consistent with research conducted in India [3] where OSC is thought to have many advantages, but is perceived to be more costly.

This review of OSC was focused on its sustainability and resiliency. OSC ranges from prefabrication of cladding panels or wood stud walls to complete prefabrication of modules complete with plumbing and electrical connections, kitchens, bathrooms, etc. The body of literature revealed that OSC systems provide many improvements to sustainable performance. Various articles focused on proving and demonstrating one or more benefits of OSC such as: reduced waste generation, worker safety, lower impact at construction site, improved quality, ability to build to improved specifications, lower environmental impact(s), etc. Each of the references uses a relevant metric to prove one or more of these benefits, the most complete of which is the LCA.

Review of the literature revealed that once OSC is viewed from the point of view of the manufacturing industry, it is found that OSC lends itself to advancement from the manufacturing sector such as lean manufacturing (construction). Moreover, with the exception of a few references, the weaknesses of OSC systems are rarely addressed. The assumption that there are weaknesses is a result of deducing that with all the benefits of OSC, the adoption of this technique by the industry has not been as expected, which leads to the belief that there are embedded weaknesses. From the review of the literature and interviews with a few proponents, it is deduced that the major weaknesses hindering the widespread uptake of OSC are that the economic benefits are not realized and that the current business models in use in the construction industry are not compatible with OSC system.

Considering sustainability's three aspects, previous researchers have found that OSC may affect all these aspects of sustainability. Lawson et al. [37] have found that waste reduction to less than 5% in a factory environment with greater potential for recycling (environmental and economic impact). They also found reduction in transport activities, (environmental, social and economic impact), noise, site disruption (environmental and social impacts), embodied energy (environmental impact) all while improving building air-tightness, thermal performance and acoustics (environmental impact) and improved safety on-site (social impact) [37]. Nahmens & Ikuma [46] found that lean construction of modular homes reduces waste by 64% (environmental impact), improves safety (social impact) and reduces production time by 31% (economic impact). Similar results were also reported by others [4,13,14,29,38,70,2]. In general benefits of modular and off-site construction have been widely reported [52].

In a further comparative study of environmental impacts of OSC (namely modular construction) and conventional construction of a 2-storey home, Quale et al. found that on average, using modular construction has lower environmental impacts than on-site construction. The same source discussed significant levels of uncertainty, however the overall trend should hold. Another interesting observation was the sensitivity of the environmental performance of modular construction systems; small changes could change the results of the OSC system performance from an environmentally friendly system to a system with negative environmental impacts. For example, if the modular construction system is manufactured in poorly insulated factories in rural settings, i.e. transportation and heating/cooling impacts are significant, the environmental impact could be the same as for traditional construction, or in severe cases, worse than a well-functioning traditional construction system. The sensitivity is particularly significant for transportation requirements and factory energy consumption [56]. This confirms the expectations that there are necessary and sufficient conditions for an OSC system to truly be more sustainable. In that same study, Quale et al. cited several studies that have investigated the sustainability (or solely environmental) effects of off-site and modular construction in Michigan [34] and Japan [48], that show similar conclusions where the overall life cycle impacts are favourable for OSC systems, when certain conditions are met.

It appears that the research and design community agree that OSC in general, the most complete of which is modular construction, is, or has the potential to be, one of the most sustainable and resilient construction systems. This statement should be proven quantitatively and scientifically. The burden of proof has been previously placed on other sustainable products, systems, assemblies and structures. The result was a variety of tools that have been devised: certification systems/rating systems, standards, academic/research-based metrics which were discussed above. None of these tools as previously discussed can measure sustainability and resilient performance.

It can be concluded from the review that OSC has significant potential in several areas relating to sustainability and resiliency. This makes it a prime candidate to be the construction method of the future. Having said that, OSC has two main challenges: (1) inability to prove improved resilient and sustainable performance in all three aspects: environmental, social and economic performance; and (2) improve adoption of this type of construction. To achieve both of these goals, the most important need is for an actual performance metric or a framework for a metric for sustainability and resiliency. This framework can be used to:

- Prove sustainability and resiliency claims, assumptions and expectations by proving improved resilient, environmental, social and economic performance.
- Use this information, particularly social and economic performance to drive adoption.
- Use the information in the metric to address weaknesses and shortcomings, and to strengthen strengths.

5. Conclusions

The review of this body of literature has demonstrated that in order to prove any claim with respect to sustainability and resiliency, or portion thereof, there is a need to choose, assign, or develop a metric, which has led to the deployment of many different metrics. Of all the metrics, LCA is currently the state-of-the-art in quantifying environmental impacts, however it has significant challenges. LCA is the only metric that employs scientific methods for measurements and criteria to evaluate impacts. Certification systems are useful and are successful at meeting their purpose, however they cannot be adopted as metrics for performance-based decisions or evaluations. Finally, OSC systems have the potential to be a sustainable and resilient construction system. In order to demonstrate this potential, a true metric or framework for a metric need to be devised. Subsequently, it can be used to prove or disprove the performance of an innovative solution, improve it, and finally encourage adoption of such solutions.

The analysis of the literature revealed a significant body of information in the fields of sustainability, environmental awareness, green buildings, etc. There is a significant amount of overlap and misuse of the terminology, however more recent publications appear to have it sorted out due to the improved uniform definition for sustainability. Having said that, the next significant gap in the literature is for the sustainability metrics, where even though the definition is uniform, the method of measuring sustainability is anything but, and rarely if ever address all aspects of sustainability as established by the definition used.

Review of other industries has revealed rational methods are put forward to assess primarily the environmental impact of sustainability. Moreover, methods for aggregating the various impacts, being environmental, social and economic, have been developed with the Canberra distance and Mahalanobis distance yielding promising results. These aggregation methods can be adapted to form a part of buildings' sustainability and resiliency metrics. The literature revealed an overall consensus that a properly designed OSC system has the potential to be more sustainable and resilient than the traditional construction techniques. However, to prove such a claim, as is the case for all buildings, a sustainability and resiliency metric is required. The literature revealed that such a framework is yet to be developed for buildings, including OSC.

For future research, there is a significant work remaining in the field of sustainability and resiliency. Even if research is successful in developing a framework to measure sustainability performance, there will certainly be gaps that require research to address specific questions, and future research will definitely be required to improve, rectify, and evolve the framework. Also, there is a need for future research to address the transfer of these metrics to the built environment. Furthermore, there is a need to conceptualize the integration of resiliency into sustainability.

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Chapter 3 – Sustainability framework for buildings via data analytics

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Sustainability; Framework; Sustainability Performance Metric (SPM); Projection to Latent Structures Partial Least Squares (PLS); Housing

Abstract

Sustainability is the most important goal to pursue in all aspects of human activity, not least of which in the built environment. Sustainability encompasses social, economic and ecological impacts which are influenced by collinear and correlated factors. A qualitative description of sustainability is a necessary but not sufficient requirement as it could be misleading and counterproductive. Accordingly, a Sustainability Performance Metric (SPM) framework was formulated using latent variable methods to manage sustainability indicators. The development of SPM was guided conceptually by sustainability principles and its implementation by objective and function statements. Single-family-detached housing was employed as a test of the concept. Corresponding datasets were generated using reliable models, specifically Athena Impact Estimator for Buildings, EnergyPlus, Building Information Modelling software, and an Input/Output socio-economic predictor. The results revealed the importance of observing all aspects of sustainability through a metric such as the SPM, the sensitivity of the SPM to the correlated factors, and the impacts of construction trends appearing in the North American marketplace on sustainability.

1. Introduction & Background

Sustainability of all human activities and environments, including the built environment, is a necessary requirement for a multitude of ecological, societal and economic reasons as reported in the literature [1–4]. It is framed as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", with the needs being equally weighted between economic needs/impacts, social needs/impacts and environmental or ecological needs/impacts [1, 5-6].

Sustainability, being three dimensional, is often represented as a Venn diagram of three circles of equal diameter [7]. Accordingly, sustainability is the union of all three dimensions, although some have interpreted it to be the intersection of the three circles in this diagram. The intersections imply that more than one dimension is necessary to be considered. Pillars is the other approach employed to represent the 3-dimensions of sustainability. This implies that the dimensions are distinct and independent, although there are clear interrelations and interactions among them [7]. Of significance is the historic origin of the three dimensions of sustainability that does not appear to be rooted in a rigorous scientific workup, and does appear to have a multitude of implications depending on the perspective of the reader [7]. For this study, the notion of three equally weighted dimensions is adapted as a guiding principle for quantifying sustainability of the built environment.

Historically, the three dimensions of sustainability have been treated separately to simplify a complex problem, such as the impact of the energy consumption of the building during occupancy on the environment [8–11]. Others have extended sustainability of the built environment to include a combination of life-cycle assessment (LCA) and life-cycle costing (LCC) [12–15]. Several studies have considered Net Present Value methods (NPV) of avoided costs or benefits, and other economic indicators in conjunction or as part of the LCC for quantifying sustainability [13, 16–18]. Recognizing that the three dimensions of sustainability, the ecological, social, and economic spheres, encompass a multitude of diverse factors and impacts, the coupling and/or linking of several factors is a must. Accordingly, the notion is extended to account for the coupling of the three equally weighted dimensions as a favourable guiding principle for quantifying sustainability of the built environment.

Based on the review of the literature in the field, where LCA and LCC are used often in academic studies as some of the most complex methods for evaluating sustainability, LCA and LCC can be considered at the forefront of the practical metrics for sustainability. The review revealed that the LCA and LCC methodology is effective in capturing ecological and economic impacts; however, they are not practical design tools. Other metrics, such as Leadership in Energy and Environmental Design (LEED) [19], Building Research Establishment Environmental Assessment Method (BREEAM) [20] and German Sustainable Building Council (German: Deutsche Gesellschaft für Nachhaltiges Bauen) DGNB certification [21] among others, practicality has mandated some subjective assessments as well as prescriptive paths. A critical review of these metrics has revealed that there is no mainstream metric or measure for sustainability of buildings that is scientific, repeatable and performance-based [1]. The review also concluded that academic-proposed measures, albeit some are more rigorous, they are not practical and do not adequately address the three dimensions of sustainability or tend to include unjustifiably subjective measures [1]. This study, which presents a holistic framework for measuring sustainability, was undertaken to overcome the challenges facing the development of sustainability metrics for building. The concept development and corresponding mathematical formulation is first presented, followed by a test of the concept of the sustainability performance metric (SPM) applied to single-family-detached housing in North America.

2. Framework for Sustainability Metric

2.1 Concept development

The proposed framework for the sustainability metric is derived conceptually from the favourable notion that all sustainability indicators; economic, social and environmental, are accounted for and equally weighted [2, 5-6]. The framework formulation is developed in two stages: Stage 1 presents the development of the holistic concept while Stage 2 addresses the mathematical equivalent of the concept. Figure 1, which provides a visual display of the proposed concept, shows that the framework comprises of two silos, indicators and life cycle. The objective and function statements set as a-priori, form the path forward to implement the sustainability indicators' requirements, and the observed variables quantified throughout the life cycle. The revealed contrast has been a major obstacle in developing a consistent and quantifiable metric for sustainability. The formulated sustainability metric framework links the two silos through abstract variables that can also be referred to as latent variables. The implementation of the sustainability indicators as an a-priori construct is guided by the corresponding objective and function statements.

Economic sustainability objective statements (ECOS):

1. Positive economic growth is the primary measure of the economic indicator in current economic systems;
2. Economic growth applies to both the public and private sectors, and should be balanced;
3. Affordability cannot be undermined by economic growth;
4. Impacts of economic growth are balanced with environmental and social impacts.

The corresponding function statements are put forward as quantifiable measures of the ECOS:

a) All indicators have to be scientifically measurable;

b) Indicators may be used to measure multiple functions’ statements;
c) Functions may be measured by the interaction of multiple indicators;
d) Indicators need to be considered for every phase of the life-cycle;
e) Economic growth can be measured via impact on real Gross Domestic Product (GDP), or value added, internal rate of return, net present value, etc. for all phases of the life cycle;
f) The balance between public and private economic growth can be measured by economic growth (ECOS1d), public funding, taxation, etc.;
g) Affordability can be measured via housing affordability indices, costs, standard of living, etc.;
h) The balance between economic growth, environmental and social impacts is measured by the interaction between all indicators across all three dimensions of sustainability.

Social sustainability objective statements (SOS):

1. The societal impact on the end-users (e.g. occupants of a building) that needs to be measured includes comfort, affordability, happiness, mental health, etc.;
2. The societal impact on surrounding neighbours and neighbourhoods that needs to be measured includes beauty, comfort, affordability, happiness, mental health, etc.;
3. The societal impact beyond the surrounding locale that needs to be measured includes city-wide, province/territory/state-wide, nation-wide, and global effects;
4. The societal impact on social fabric (e.g. culture, politics, etc.) needs to be measured to address the societal reactions to large changes;
5. Social impacts are balanced by consideration of economic and environmental impacts.

The corresponding function statements are put forward as quantifiable measures of the SOS:

a) All indicators have to be scientifically measurable;
b) Indicators may be used to measure multiple functions’ statements;
c) Functions may need to be measured by the interaction of multiple indicators;
d) Indicators need to be considered for every phase of the life-cycle;
e) The societal impact on the end-users can be measured using comfort indices based on ability to achieve the needs (transportation, shopping, etc.), fiscal impacts, indicators with known effects on mental health, etc.;

f) The societal impact on surrounding neighbours and neighbourhoods can be measured by measuring beauty, compatibility, impact on value of neighbouring projects, risks to neighbours, traffic impacts, etc.;

g) The societal impact beyond the surrounding locale can be measured using local and global job creation, salaries, working conditions, health and safety, etc.;

h) Balance between social impacts and environmental and economic impacts is measured by the interaction between all indicators across all three dimensions of sustainability.

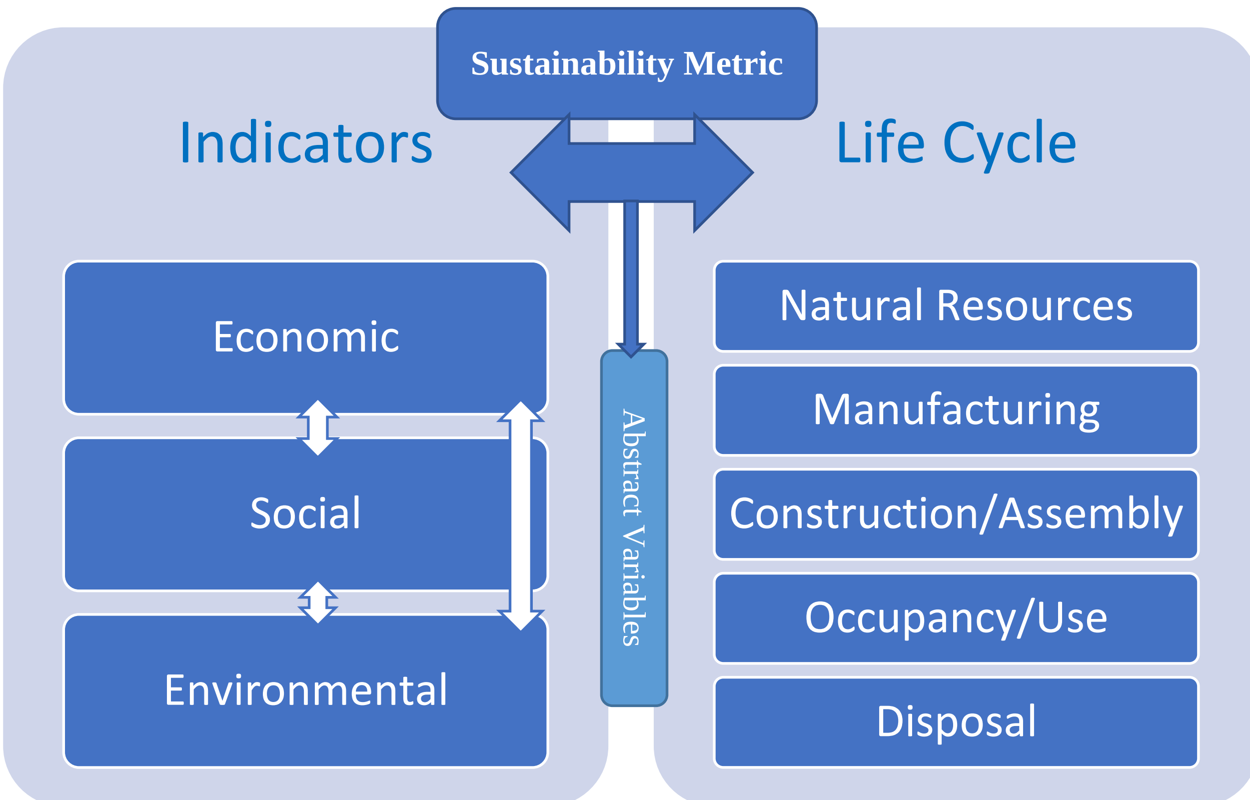

Figure 1. Conceptual representation of the sustainability framework metric.

Environmental sustainability objective statements (ENOS):

1. The amount of resources used (land, material, energy, water, air, etc.) has to be minimized and used efficiently, and thus constitutes an environmental indicator;
2. Pollutants that impact air quality and climate change have to be minimized;
3. Pollutants that impact water quality have to be minimized;
4. Pollutants that impact land and habitat quality have to be minimized;

5. Environmental impacts are balanced with social and economic impacts.

The corresponding function statements are put forward as quantifiable measures of the ENOS:

a) All indicators have to be scientifically measurable;
b) Indicators may be used to measure multiple functions' statements;
c) Functions may need to be measured by the interaction of multiple indicators;
d) Indicators need to be considered for every phase of the life-cycle;
e) The amount of resources used can be measured by material volume or mass, energy consumption, water consumption, etc.;
f) The impact on air quality and climate change can be measure by LCA parameters such as global warming potential, smog potential, ozone depletion, etc.;
g) The impact on water quality can be measured by eutrophication, grey and black water production, etc.;
h) The impact on habitat and land quality can be measured by acidification, loss of habitat, etc.;
i) Balance between environmental impacts and economic and social impacts is measured by the interaction between all indicators across all three areas of sustainability.

Stage 2 of the framework introduces abstract variables to link the two silos. By employing abstract or latent variables, the mathematical obstacles that arise when dealing with multicollinearity due to intercorrelated or inter-associated variables are mitigated. Accordingly, the partial least squares (PLS) statistical method [22–27], which captures the latent variables, is adopted to derive the mathematical model. Latent variables may not be quantified, measured, or observed themselves; however, they can be expressed mathematically. The PLS method or algorithm is best suited to extract these latent variables and to utilize them to gain insights into their interactions with each other, and to point out how a desired performance level could be achieved. For the postulated framework, PLS method is used to create a scientific, repeatable and objective results. In brief, the characteristics that allow the PLS method to extract, quantify, and measure the latent variables that constitute sustainability are noted below:

- Ability to handle collinear inputs and outputs (i.e. handle the interactions and couplings)
- Can achieve the goals using a relatively smaller dataset

- Despite being a statistical algorithm, it is not a black-box approach, which allows the user to gain insights into the system interactions
- Does not require the definition of assumed functions beyond selecting the higher-order variables that are to be considered (arguably only limited by the available dataset)
- It belongs to the family of linear models, which allows for selecting the appropriate underlying model to be used for the linear programming exercise (linear optimization), to calculate a global optimum.

2.2 Mathematical Formulation

Mathematically, the PLS equations are expressed as:

$$\hat{Y}^T = \beta \cdot \hat{X}^T$$

Where, $\hat{Y}^T$ is the transpose of the estimated output vector as a result of a set of inputs described by $X\ (or\ \hat{X}^T)$, with all values being centered and scaled. $\hat{Y}^T$ has dimensions of M × 1 where M is the number of output variables in the model. $\hat{X}^T$ is the transpose of the input variables vector used to calculate the estimations $\hat{Y}^T$, with all values being centered and scaled. $\hat{X}^T$ has dimensions of K × 1 where K is the number of input variables in the model. β is the coefficient matrix which is calculated by the PLS model and is referred to as the model. The coefficient matrix, β, has dimensions M × K. Every element in β describes the relationship between an input variable and output variable. Noting that the X-vector is a description of the building or any built structure, then each column of β describes a specific output or performance indicator for the building described by X. The result is that the subsequent sustainability performance metric (SPM) describes the performance across all indicators created from the outputs of the PLS model. This metric, which is directly related to the performance of all sustainability output indicators included within the model, is described by a new $\hat{X}$ vector whose sustainability indicator is either greater than 1 which indicates a worse than average overall sustainability performance or lesser than 1 indicating a better than average overall sustainability performance, i.e. lower number of the sustainability indicator reflects better overall sustainability performance.

The model derivation steps are as follow:

STEP 1. Centre and scale the $\hat{X}$-vector by subtracting the mean, $\bar{X}$, and dividing by the standard deviation, σ_X,

$$\hat{X}_{centered} = \frac{\hat{X} - \bar{X}}{\sigma_X}$$

STEP 2. Multiply each $\hat{X}_k$ by the corresponding $\beta_{k,m}$ with k and m being the input and output, respectively.

STEP 3. Calculates the centred and scaled outputs,

$$\hat{y}_m = \hat{X}_k \times \beta_{k,m}$$

STEP 4. Un-centre and un-scale the $\hat{y}_m$values by multiplying by the standard deviation, σ_Y and add the mean, $\bar{Y}$.

STEP 5. Normalize each of the outputs by dividing by the mean ${\hat{y}_m}/{\bar{y}_m}$.

STEP 6. Equalize the weighted average with the environmental impact equals 1/3 of the total weight and the social and economic impacts equal to 2/3 of the weight forming the sustainability performance metric (SPM):

$$SPM = \left\{\sum_{m=1}^{Menv} \frac{\hat{y}_{m-env}}{\bar{y}_{m-env}}\right\} \Big/ 3 \times M_{env} + 2 \times \left\{\sum_{m=1}^{Msec} \frac{\hat{y}_{m-sec}}{\bar{y}_{m-sec}}\right\} \Big/ 3 \times M_{sec}$$

in which M_{env} is the number of environmental outputs, $\hat{y}_{m-env}$ is the estimated environmental output values calculated from the model, $\bar{y}_{m-env}$ is the mean of the environmental output from the model dataset, M_{sec} is the number of social and economic outputs, $\hat{y}_{m-sec}$ is the estimated social and economic output values calculated from the model, and $\bar{y}_{m-sec}$is the mean of the social and economic output from the model dataset.

3. Application to Sustainability of Buildings

The postulated SPM is holistic and all encompassing. However, its application is contingent on the availability of measurable observed variables or data. For buildings, data can be generated using reliable models or collected from the literature. For this study, models are adopted to generate the data. Specifically, Athena Impact Estimator for Buildings [28], EnergyPlus [29], Building Information Modelling software (BIM), and an Input/Output socio-economic predictor [30-31] are employed. The Athena Impact Estimator for Buildings [28] provides a life-cycle assessment (LCA) in accordance with the appropriate standards [32-33]. The model inputs are the building's geometry, constructions, location, service life, and it produces a bill of material, as well as the following outputs: Global warming potential, Acidification potential, Human health particulate, Eutrophication potential, Stratospheric ozone depletion potential, Smog potential, Total primary energy, Non-renewable energy, and Fossil fuel consumption. An Input/Output socio-economic impact model developed by one of the authors for Econometric Research Limited is employed to estimate the economic impacts associated with capital and operational expenditures. The impact indicators include GDP, Labour Income, Employment and Taxes by tax and level of government collecting it. A three-dimensional perspective is used where the total impact by measure is divided into direct, indirect and induced impacts. Furthermore, the model calculates within the same platform the economic, social and environmental impact. EnergyPlus [29] is a comprehensive dynamic energy modelling software used to calculate the building energy consumption during occupancy. This modelling tool quantifies in detail all the energy end-uses while accounting for the building geometry, use and location. The BIM software is used to model the building in detail and generate various outputs that are used as the inputs into the LCA software, energy modelling software, the econometrics software, and others.

Other models such as that of water consumption are also used to generate additional data to quantify other indicators, impacts and interactions. The social indicators and corresponding impacts are found to be the most challenging to quantify in a scientific, repeatable and objective manner. However, this metric is conducive to evolution to which new indicators can be added.

4. Proof of Concept – Sustainability of Single-Family-Detached Housing

In this study, as a proof of the applicability of the concept of the sustainability metric framework, a prototype for single-family-detached housing is developed. Accordingly, input datasets for PLS model need to be generated.

4.1 Sustainability Factors (Inputs) and Indicators (Outputs)

For single-family-detached housing, Tables 1 and 2 list the inputs and outputs utilized in the development of the SPM metric. For every variable, a range is specified to cover typical single-family houses built in North America. The ranges along with a description of each input factor are also given in Table 1. The corresponding dataset which yields the house characteristics is generated using a full saturated fractional factorial design of experiment statistical method [27, 34].

Table 1. Inputs – Measurable factors impacting sustainability.

Input Factors	Range	Description
Floor Footprint Area (m^2)	110 – 440	The area of the footprint of the house.
Number of Storeys	1 – 2	Number of storeys, not including the basement, of the house.
Number of Occupants	2 – 8	Number of people occupying the building.
Clear Wall Height (m)	2.44 – 3.05	The vertical distance between the top of the floor to the underside of the ceiling structure.
Number of Basements	0 – 1	The number of floors below ground. The basement is assumed to be constructed from poured concrete or masonry block.
Luxury Level	2 – 10	On a scale from 2 to 10, where 2 is the most commercial grade (lowest cost), while 10 is maximum reasonable luxury within the typical North American market.
Percentage Brick Façade (%)	0 – 100	Percentage of the façade area that would be clad with brick. The brick is assumed to be approximately 89 mm thick and stacked.
Percentage EIFS Façade (%)	0 – 100	Percentage of the façade area that would be clad with an exterior insulation and finish (EIFS) system, constituting expanded polystyrene and a stucco-type finish.
Percentage Siding Façade (%)	0 – 100	Percentage of the façade area that would be clad with siding. The siding is assumed to be 16 mm thick pine board cladding.

Percentage Stone Façade (%)	0 – 100	Percentage of the façade area that would be clad with artificial concrete stone. The concrete stone is assumed to be approximately 89 mm thick and stacked.
Occupancy Time (hrs /day)	8 – 22	Number of hours that the occupants (people) that the building design is expected or intended to accommodate. For example, a retiree's home would be expected to have a higher occupancy time as opposed to young professionals.
Service Life (years)	25 – 100	The number of years that the house is designed to be in service.
HDD18	130 – 10,416	Heating degree days at a base of 18°C at the location that the house is built at.
CDD18	67 – 4,458	Cooling degree days at a base of 18°C at the location that the house is built at.
City Population	2,971 – 5,928,040	The census populations for that city/town/village at which the house is built at. This could affect transportation distances and other economic impacts.
Surrounding Area Percentage Brick Façade (%)	0 – 100	The surrounding houses' façade area that have a brick-look facing the proposed house. This is intended to attempt to capture aesthetics. It is not currently a strong factor.
Surrounding Area Percentage EIFS Façade (%)	0 – 100	The surrounding houses' façade area that have an exterior insulated and finish system or stucco-look facing the proposed house. This is intended to attempt to capture aesthetics. It is not currently a strong factor.
Surrounding Area Percentage Siding Façade (%)	0 – 100	The surrounding houses' façade area that have a siding-look facing the proposed house. This is intended to attempt to capture aesthetics. It is not currently a strong factor.
Surrounding Area Percentage Stone Façade (%)	0 – 100	The surrounding houses' façade area that have a stone-look facing the proposed house. This is intended to attempt to capture aesthetics. It is not currently a strong factor.
Total Area of Windows on all Façades (m^2)	19 – 54	Total area of all windows and doors (excluding opaque doors) on the total façade.
Percentage of Façade facing South (%)	16 – 29	Total area-based percentage of all windows and doors (excluding opaque doors) on the south façade relative to the total façade.
South Façade Area (m^2)	22 – 94	Total area of all the façade facings south.
Number of Low Flow Faucet Fixtures	0 – 7	Number of low flow faucets fixtures, excluding tubs and showers. This mainly impacts water consumption.
Number of Dual Flush Toilets	0 – 4	Number of dual flush toilets. This mainly impacts water consumption.
Number of Low Flow Shower/Tub Fixtures	0 – 4	Number of low flow shower and tub fixtures. This mainly impacts water consumption.

Percentage Building Area-to-Lot-Area Ratio (Coverage) (%)	10 – 75	The house footprint area divided by the total lot area expressed as a percentage.
Overall Attic U-value (with film) ($W/m^2.K$)	0.185 – 0.301	The thermal transmittance value (U-value) of the insulation of the ceiling structure with film. All datapoints in this model have attic spaces between the ceiling and the roof.
Overall Wall U-value (with film) ($W/m^2.K$)	0.153 – 0.531	The thermal transmittance value (U-value) of the insulation of the wall cavity with film.
Window U-value ($W/m^2.K$)	1.249 – 5.548	The thermal transmittance value (U-value) of the insulation of the windows with film.
Window SHGC	0.202 – 0.801	The solar heat gain coefficient of windows.
Roof Solar Absorptance	0.25 – 0.95	The solar absorptance of the roofing material's outwards surface.
Wall Solar Absorptance	0.25 – 0.95	The solar absorptance of the exterior wall material's outwards surface.
Heat Recovery (HRV) Efficiency (%)	0 – 90	The efficiency of the heat recovery system. If no HRV is installed, a zero was entered.
Setbacks	0 – 1	If the design is intended to have setbacks on the thermal control of the conditioned space, a 1 should be entered, and if not, a 0 should be entered.
Air Tightness (ACH at atm)	0.075 – 0.520	The air tightness expressed as air changes per hour at atmospheric condition, intended to quantify how air tight the building envelope is.
Percentage of fresh air from controlled source (%)	0 – 100	This related to control the source of fresh air entry, e.g. a well thought out inlet for an HRV versus no HRV and depending on natural ventilation via air infiltration and exfiltration.
Wood Structural Material Volume (m^3)	1 – 85	The volume of wood structural material in cubic meters for the house design.
Concrete Structural Material Volume (m^3)	58 – 310	The volume of concrete structural material in cubic meters for the house design.
Steel Structural Material Volume (m^3)	0 – 3	The volume of steel structural material in cubic meters for the house design.
Materials Sourced Locally	0 – 1	This determines whether or not priority is being given to locally sourced materials. This refers also to products and systems.
Materials Manufactured Locally	0 – 1	This determines whether or not priority is being given to locally manufactured materials. This refers also to products and systems.
Materials Assembled Locally	0 – 1	This determines whether or not priority is being given to locally assembled materials. This refers also to products and systems.

Percentage Prefabricated	0 – 100	What percentage of the building being prefabricated? For complete site-built houses it is 0, and for completely prefabricated, modular, and off-site construction, it is 100.
Controlled Site Entrance and Exit	0 – 1	This determines whether or not site entrance and exit controls are in-place, intended to capture quality of the construction work.
Review of Public Safety Performed	0 – 1	This determines whether or not a public safety review is in-place, intended to capture impact on public during construction.
Review of Worker Safety Performed	0 – 1	This determines whether or not a review of worker safety is in-place, intended to capture impact on workers.
Scaffolding and Protection Equipment Used	0 – 1	This determines whether or not a quality control (QC) system is in-place, intended to capture quality of the work if quality control is being considered.
Construction QC in-place	0 – 1	This determines whether or not a quality control (QC) system is in-place, intended to capture quality of the work if quality control is being considered.
Number of Inspections by Regulators	2 – 10	The number of inspections planned to be conducted by regulators, intended to capture quality of the work.
Number of Inspections by Professionals	0 – 10	The number of inspections planned to be conducted by professionals, intended to capture quality of the work.

The outputs selected for the study are based on a balance between their importance and relevance to sustainability, their coverage of the three dimensions of sustainability, and the practical ability to collect the data. Environmental or ecological impact metrics are widely available and practical to calculate for the main impacts such as energy use and life cycle assessments. Economic impact metrics are quantified using econometric models. However, specialized knowledge and experience in economics is required to generate the dataset and to provide insights into the results. Finally, social indicators are the most difficult to quantify by both practitioners and academics alike. The social impacts for this prototype are included through other measures such as employment and salaries. The list of outputs and corresponding range for detached single-family housing is given in Table 2.

Table 2. Outputs – Group of impacts that together describe sustainability.

	Output Responses	Range	Description
1.	Total Annual Energy Consumption (kWh)	18,085 – 95,690	Estimated total annual energy consumption of the whole house according to EnergyPlus [29]. *Objectives: ECOS4, ENOS1-5*
2.	Annual Energy Use Intensity – EUI (kWh/m^2)	69 – 399	Estimated total annual energy consumption of the whole house divided by the total area of the conditioned space according to EnergyPlus [29]. *Objectives: ECOS4, ENOS1-5*
3.	Global Warming Potential (kg CO_2 eq.)	40,902 – 182,790	Global warming potential estimated via Athena Impact Estimator for Buildings [28]. This is a widely accepted reference measure expressed as an equivalency to CO_2, in kg CO_2 equivalent. *Objectives: ENOS1, 5*
4.	Acidification Potential (kg SO_2 eq.)	271 – 983	A regional negative impact on human health when due to high concentrations of NOx and SO_2 occur, estimated using Athena Impact Estimator for Buildings. For air and water emission, an equivalency is calculated based on H+ effect on a mass basis [28]. *Objectives: SOS1-3, ENOS2,3*
5.	Human Health (HH) Particulate (kg PM2.5 eq.)	82 – 331	A measure of various sizes of particulate matter which have a negative impact on human health as estimated by Athena Impact Estimator for Buildings [28]. *Objectives: SOS1-3, ENOS2*
6.	Eutrophication Potential (kg N eq.)	13.7 – 50.3	A measure of "the fertilization of surface waters by nutrients that were previously scarce," as estimated by Athena Impact Estimator for Buildings, as an equivalent mass of nitrogen (N) [28]. *Objectives: ECOS2, SOS1-3, ENOS4*
7.	Stratospheric Ozone Depletion Potential (kg CFC-11 eq.)	0.00019 – 0.00123	A measure for estimating the negative impacts on the ozone layer as a result of the release of ozone depleting substances (CFCs, HFCs, and halons) estimated by Athena Impact Estimator for Buildings as an equivalency by mass to CFC-11 [28]. *Objectives: ECOS2, SOS1-3, ENOS2*
8.	Smog Potential (kg O_3 eq.)	5288 – 18,489	A measure of the photochemical ozone creation potential as estimated by Athena Impact Estimator for Buildings as an equivalency by mass to O_3 [28]. *Objectives: ENOS2*
9.	Total Primary Energy (MJ)	824,466 – 3,334,191	A measure of embodied energy, "includes all energy, direct and indirect, used to transform or transport raw materials into products and buildings, including inherent energy contained in raw or feedstock materials that are also used as common energy sources," as well as "the indirect energy use associated with processing, transporting, converting

		and delivering fuel and energy," as estimated by Athena Impact Estimator for Buildings [28]. *Objectives: ECOS4, SOS2, ENOS1-5*
10. Non-Renewable Energy (MJ)	704,480 – 3,206,125	A measure of a "subtotal of Total Primary Energy that includes all fossil fuel energies and nuclear energy" as estimated by Athena Impact Estimator for Buildings [28]. *Objectives: ECOS4, SOS2, ENOS1-5*
11. Fossil Fuel Consumption (MJ)	653,148 – 2,867,226	A measure of a "subtotal of Total Primary Energy, by energy type, that includes all fossil fuel energies" as estimated by Athena Impact Estimator for Buildings [28]. *Objectives: ECOS4, ENOS1-5*
12. Initial Expenditures ($) / Value Added ($)	0.175 – 1.299	Ratio of initial expenditures to value added, where initial expenditures indicate the amount of expenditures directly made by the builders and owners of the house. It is these expenditures that typically drive the impact results. The value added represents net output generated by the initial expenditures. It is typically the sum of wages, rent, interest and profits in addition to indirect business taxes and depreciation minus subsidies. The value added is estimated via the econometric model. *Objectives: ECOS2-4, SOS1,5*
13. Initial Expenditures ($) / Gross Output ($)	0.063 – 0.465	Ratio of initial expenditures to the gross output where initial expenditures indicate the amount of expenditures directly made by the builders and owners of the house. It is these expenditures that typically drive the impact results. The gross output represents the total economic activity generated by the activity. The gross output is estimated via the econometric model. *Objectives: ECOS2-4, SOS1-5*
14. Initial Expenditures ($) / Salary ($)	0.250 – 1.940	Ratio of initial expenditures to salaries or wages paid, where initial expenditures indicate the amount of expenditures directly made by the builders and owners of the house. It is these expenditures that typically drive the impact results. The salary represents the total amount of expenditures paid as salaries to support the activity. The salary is estimated via the econometric model. *Objectives: ECOS2-4, SOS1-5*
15. Initial Expenditures ($) / Employment (FTE)	12,100 – 96,798	Ratio of initial expenditures to value added, where initial expenditures indicate the amount of expenditures directly made by the builders and owners of the house. It is these expenditures that typically drive the impact results. The employment refers to the total person years (full-time equivalent jobs) generated by the activity of constructing the house. The employment is estimated via the econometric model. *Objectives: ECOS2-4, SOS1-5*

16.	Initial Expenditures ($) / Taxes ($)	0.392 – 3.040	Ratio of initial expenditures to taxes paid, where initial expenditures indicate the amount of expenditures directly made by the builders and owners of the house. It is these expenditures that typically drive the impact results. The taxes include personal income taxes, corporate profit taxes, local property and business taxes, etc. The taxes are estimated via the econometric model. *Objectives: ECOS2-4, SOS1-5*
17.	Initial Expenditures ($) / Imports ($)	0.409 – 3.175	Ratio of initial expenditures to imports, where initial expenditures indicate the amount of expenditures directly made by the builders and owners of the house. It is these expenditures that typically drive the impact results. The imports represent the goods and services acquired from outside the local province or state to sustain the activities and industry. They essentially represent leakages from the local province or state. The imports are estimated via the econometric model. *Objectives: ECOS2-4, SOS1-5*
18.	Annual Water Consumption (kL/year)	185 – 591	This is the estimated total annual water consumption of the whole house (its occupants) using an online water consumption estimator [35]. *Objectives: ENOS3-5*

4.2 Dataset

The first step is to determine the minimum number of data points required to capture the influence of 50 input factors. The results reveal a resolution III (Res III) experimental design implying that the main factors are confounded with higher order interactions. This resolution level is typically used for initial studies to understand the mechanisms of the studied systems. Resolution IV and V are recommended for optimization and systems design. For this study, it was clear that the data collection would pose the main challenge. As such, a Resolution III is selected to develop the framework, with future work expected to target high-resolution experimental designs. Accordingly, the 2_{III}^{50-44} saturated experimental design requires a minimum of 64 observations.

4.3 SPM Development for Single-Family-Detached Housing

The PLS model was developed using 50 input factors, 18 outputs, and 64 observations as the training set. The significance of the factors are determined by investigating the variables' coefficients or variables' importance for projection (VIP) plots [23, 26, 36]. The model is evaluated statistically by calculating the Root Mean Squared Error of Estimation (RMSEE) and the coefficient of determination (R^2). The values of RMSEE and R^2 for each of the outputs, given in Table 3, reveal the goodness of fit. Moreover, the errors reveal a variance less than 15% for the outputs measuring the ecological impact and about 26% for the outputs measuring social and economic impacts. Given the complex nature of sustainability and the uncertainty associated with the corresponding datasets, max RMSEE values of 15%, 26% and 26%, corresponding to ecological, economic and social impacts, are representative and deemed acceptable for this study.

Table 3. RMSEE and R^2 values of the PLS model for each of the outputs.

Output Responses	Mean	RMSEE (%)	R^2
1. Total Annual Energy Consumption (kWh)	49,041	14.0	0.90
2. Annual Energy Use Intensity – EUI (kWh / m^2)	157	18.5	0.84
3. Global Warming Potential (kg CO_2 eq.)	92,257	11.5	0.92
4. Acidification Potential (kg SO_2 eq.)	553	10.4	0.93
5. HH Particulate (kg PM2.5 eq.)	161	11.9	0.92
6. Eutrophication Potential (kg N eq.)	27.9	12.1	0.89
7. Ozone Depletion Potential (kg CFC-11 eq.)	0.000472	26.9	0.73
8. Smog Potential (kg O_3 eq.)	10,265	13.1	0.89
9. Total Primary Energy (MJ)	1,532,763	9.7	0.95
10. Non-Renewable Energy (MJ)	1,441,343	9.7	0.95
11. Fossil Fuel Consumption (MJ)	1,312,416	10.1	0.95
12. Initial Expenditures (\$) / Value Added (\$)	0.50	28.8	0.89
13. Initial Expenditures (\$) / Gross Output (\$)	0.18	28.8	0.89
14. Initial Expenditures (\$) / Salary (\$)	0.76	25.6	0.91
15. Initial Expenditures (\$) / Employment (FTE)	37,499	26.5	0.91
16. Initial Expenditures (\$) / Taxes (\$)	1.2	25.8	0.91
17. Initial Expenditures (\$) / Imports (\$)	1.25	25.6	0.91
18. Annual Water Consumption (kL / year)	369	10.5	0.95

4.4 SPM Prototype for Single-Family-Detached Housing

For a demonstration of SPM for single-family-detached housing, 3 houses representing various common designs including a “commercial-grade” house (House 1), “commercial-grade-plus” house (House 2), and a high-performance house (House 3) are selected. The commercial-grade house is one whose properties have been selected to be closest to minimum code, with a geometry that is expected to result in poor sustainable performance. On the other hand, the commercial-grade-plus house has average properties intended to capture typical practices that are considered good practice, and improved geometry and layout. Finally, a high-performance house has properties intended to capture current best practices. All three levels of performance are relative to North American construction practices. Tables 4 and 5 list the corresponding input data and output indicators for the three houses, respectively.

Table 4. Input data for the 3 houses representing different sustainability levels.

Input Factors	House 1	House 2	House 3
1. Floor Footprint Area (m^2)	200	150	125.00
2. Number of Storeys	1	2	2
3. Number of Occupants	2	4	4
4. Clear Wall Height (m)	3.05	2.44	3.05
5. Number of Basements	1	0	0
6. Luxury Level	10	2	10
7. Percentage Brick Façade (%)	0	25	0.00
8. Percentage EIFS Façade (%)	0	25	50.00
9. Percentage Siding Façade (%)	42	25	50.00
10. Percentage Stone Façade (%)	58	25	0.00
11. Occupancy Time (hrs /day)	22	16	16
12. Service Life (years)	100	25	100
13. HDD65	8213	8213	4500
14. CDD65	425	425	700
15. City Population	3548	3548	1,000,000

16. Surrounding Area Percentage Brick Façade (%)	0	50	50.00
17. Surrounding Area Percentage EIFS Façade (%)	0	0	0.00
18. Surrounding Area Percentage Siding Façade (%)	0	0	0.00
19. Surrounding Area Percentage Stone Façade (%)	100	50	50.00
20. Total Area of Windows on all Façades (m^2)	30.02	45.00	35.00
21. Percentage of Façade facing South (%)	28.39	28.39	28.39
22. South Façade Area (m^2)	68.67	68.67	68.67
23. Number of Low Flow Faucet Fixtures	0	0	0
24. Number of Dual Flush Toilets	0	0	0
25. Number of Low Flow Shower/Tub Fixtures	4	4	4
26. Percentage Building Area-to-Lot-Area Ratio (Coverage) (%)	75	75	75
27. Overall Attic U-value (with film) ($W/m^2.K$)	0.2600	0.2000	0.3000
28. Overall Wall U-value (with film) ($W/m^2.K$)	0.1545	0.1700	0.2500
29. Window U-value ($W/m^2.K$)	5.5470	5.3000	4.0000
30. Window SHGC	0.2220	0.5000	0.8000
31. Roof Solar Absorptance	0.25	0.25	0.25
32. Wall Solar Absorptance	0.25	0.25	0.25
33. Heat Recovery (HRV) Efficiency (%)	90	90	90
34. Setbacks	1	1	1
35. Air Tightness (ACH at atm)	0.0750	0.0750	0.1500
36. Percentage of fresh air from controlled source (%)	100	100	100
37. Wood Structural Material Volume (m^3)	84.77	84.77	84.77
38. Concrete Structural Material Volume (m^3)	218.34	218.34	218.34
39. Steel Structural Material Volume (m^3)	0.24	0.24	0.24
40. Materials Sourced Locally	0	0	0
41. Materials Manufactured Locally	1	1	1
42. Materials Assembled Locally	1	1	1
43. Percentage Prefabricated	100	100	0
44. Controlled Site Entrance and Exit	1	1	1
45. Review of Public Safety Performed	0	0	0
46. Review of Worker Safety Performed	0	0	0

47. Scaffolding and Protection Equipment Used	0	0	0
48. Construction QC in-place	0	0	0
49. Number of Inspections by Regulators	10	10	10
50. Number of Inspections by Professionals	10	10	10

Table 5. Output indicators to the three houses.

Sustainability Indicators	**House 1**	**House 2**	**House 3**
Total Energy [kWh]	52,922	40,164	33,863
Energy Per Total Building Area [kWh/m^2]	126	135	114
Global Warming Potential (kg CO_2 eq.)	131,811	83,987	115,411
Acidification Potential (kg SO_2 eq.)	820	556	735
HH Particulate (kg PM2.5 eq.)	267	180	237
Eutrophication Potential (kg N eq.)	39	29	36
Ozone Depletion Potential (kg CFC-11 eq.)	0.000748	0.000623	0.000761
Smog Potential (kg O_3 eq)	14,535	9,746	12,789
Total Primary Energy (MJ)	2,543,582	1,676,374	2,195,900
Non-Renewable Energy (MJ)	2,361,989	1,515,417	2,050,646
Fossil Fuel Consumption (MJ)	2,193,179	1,438,109	1,921,201
Initial Expenditures / Value-Added	1.196	1.001	0.236
Initial Expenditures / Gross-Output	0.428	0.359	0.085
Initial Expenditures / Salary	1.767	1.493	0.309
Initial Expenditures / Employment ($/1 FTE)	88,097	74,248	14,812
Initial Expenditures / Taxes	2.770	2.339	0.485
Initial Expenditures / Imports	2.892	2.443	0.506
Annual Water Consumption (kL/year)	190	262	260
SPM value	**2.02**	**1.65**	**0.69**

Design of House 1 has a 2.02 SPM value. As per the SPM design, this implies that it has twice the negative impacts on the environment, economy, and society. This can be said because all three aspects are of equal weight within the metric. Investigating the measure further, which is possible as a result of the non-black-box nature of the metric, the properties of the house result in high energy consumption while still having negative life-cycle assessment properties, indicating inefficient use of materials. Furthermore, the inefficient use of materials resulted in the economic and social impacts also contributed to the low performance. This finding is consistent with what design is known or would be currently considered a non-sustainable design. The major contribution is the large area of the façade (large area on a single storey), nonoptimal insulation levels, and the cladding types used. The colder climate exaggerates the effects for this particular type of construction. This demonstrates the sensitivity of the SPM to climate, embodied energy, costs, and other factors.

Design of House 2 yielded an improved performance by decreasing the footprint, increasing the number of storeys, adding more insulation, and lowering the ceiling height. Despite these changes, the corresponding SPM value of 1.65 reveals that House 2 is also among the low-performance sustainability category. This is mostly due to the low design service life of 25 years versus 100 years, and the increased percentage of glazing, demonstrating the sensitivity of the SPM to these factors as well. By analysing the details of the SPM calculated, it is observed that the environmental factors are slightly better than average, while the economic and social indicators have not improved relative to House 1 for the reasons mentioned. This clearly demonstrates the importance of considering all facets of sustainability, and energy consumption in combination with LCA is still insufficient to capture properly sustainable performance.

House 3 whose SPM of 0.69 can be considered a high performer since it is around 30% better than the average performer (average performance relative to the underlying dataset would have an SPM of 1.0). The design achieved a high-performance by balancing various attributes such as orientation, slight reduction in area, improving windows, etc. Furthermore, by reducing uncontrolled air infiltration, which is typically a sign of quality of construction and results in energy savings typically achieved with minimal additional materials being used, this improves overall sustainability performance. By investigating the various sustainability indicators within the SPM, the energy consumption is significantly below average, at the cost of worsening of the environmental impacts measured by the LCA. This is expected because of the increased utilization of energy-intensive materials. The additional costs of these materials; however, also have an improved impact on the economy and social indicators by creating additional wealth, jobs, salaries, taxes, etc. This once again demonstrates (1) the sensitivity of the SPM metric to the various variations typically made during the design process, and (2) the need to consider all aspects of sustainability which often yields different results from considering only one category of impacts.

In summary, the analysis of the examples provided includes the following considerations:

- SPM is consistent directionally with common knowledge and intuition (e.g. air tightness improves energy efficiency with minimal additional material use), confirmed by the ability to investigate the intermediate calculations within the metric and underlying model.
- The SPM is able to numerically calculate and balance the environmental, social and economic impacts of a specific design.
- The SPM is sensitive to all factors that are well-captured in the underlying dataset.

In the previous examples, the sensitivity, efficacy, and effectiveness of the SPM metric and framework were presented. For a deeper investigation, a univariate analysis of the underlying model is presented for ease of visualization. Figures 2 and 3 show how the input data, namely the footprint area, number of storeys, number of occupants, clear wall height, basement or not, luxury level, type of cladding on the façades, impacts the SPM values. The SPM values shown on the y-axis reveal the significance of the input (centred and scaled on the x-axis), where the slope of the line shows the rate at which changes occur. Negative rate of change indicates a positive impact on sustainability, and vice versa. A lack of slope indicates that either (1) the factor has minimal effect on sustainability, or (2) the dataset, and the subsequent SPM prototype, are insensitive to the factor effect.

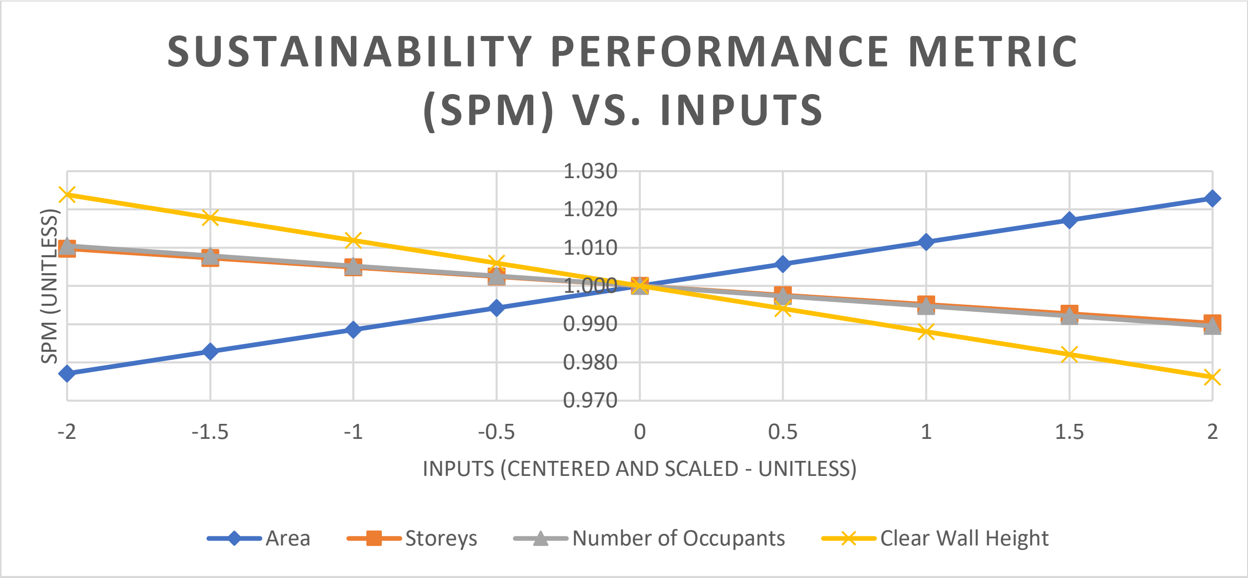

Figure 2. Impact of various factors on SPM values in centred and scaled units (unitless).

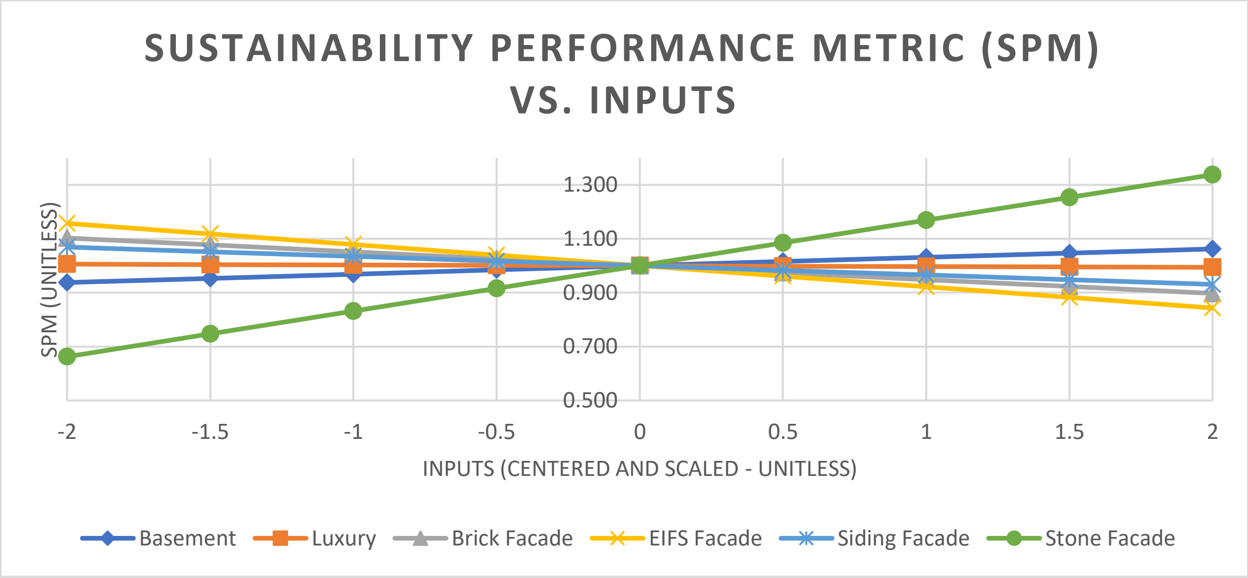

Figure 3. Impact of various factors on SPM values in centred and scaled units (unitless).

Figure 2 demonstrates that an increase in the storey height has a negative impact on sustainability, due to the fact that it would result in a large increase in energy consumption and materials used, not offset by the economic and social benefits. Increasing the number of occupants has a slight negative trend on sustainability, due to the negative economic and social impact not being offset by the ecological benefits. Also, the underlying dataset results in an SPM insensitive to capture social benefits of having an optimal number of occupants within a space. As well, increasing the number of storeys results in a slight negative impact on sustainability associated with the increase in material usage. The area, surprisingly has a positive effect on sustainability, due to the fact that the economic and social benefits, as measured in the SPM prototype, outweigh the environmental impacts. This explains the trends associated with the construction driving forces in the market. As with all factors, the analysis here is only applicable within the range of the underlying dataset.

Figure 3 investigates the impact of other factors. It demonstrates the small impact of having a basement, where increased energy consumption and environmental impacts are offset by economic aspects as measured in the dataset. The insensitivity to the luxury level is likely due to the dataset not being sufficiently varied and sensitive to that factor. As for the cladding type, the SPM metric appears to be impacted mostly by the environmental factors, specifically embodied energy, with the exception of concrete stone, where the economic impacts are more significant.

The above analyses demonstrate the various ways the SPM can be used in design, regulation, optimization, and other decision-making exercises related to sustainability. Furthermore, the importance of observing all aspects of sustainability demonstrated, and by doing that explains several of the construction trends that appeared in the North American marketplace. The benefit of applying the same framework presented in this study with further improvements to the data collected (both in quality and size) is clear and motivating of future work, along with applying the same framework to human activities other than the built environment.

5. Conclusions

A framework for quantifying the sustainability of built environment referred to as the Sustainability Performance Metric (SPM) was developed in this study. The conceptual development of the framework was guided by two principles, sustainability is a three-dimensional measure where economic, social and ecological variables are integrated and where the dimensions are equally weighted and coupled. The concept was mathematically formulated using the PLS method where latent variables provide the link between the indicators and life cycle measures. Moreover, objective and function statements were devised to manage the sustainability indicators.

The mathematical derivation and the step by step procedure provided as a framework for SPM were applied to a detached single-family housing as a proof of concept. The model predictions were shown to be accurate and precise using RMSEE and R^2. The application of SPM to detached single family housing was demonstrated using 3 houses. An SPM value greater than 1 implies poor performance, equal to 1 average performance and less than 1 good performance. Computed SPM values were found to adequately describe the sustainability of the houses by capturing the varying coupled impacts of the input variables as well as being able to reconcile all three aspects of sustainability simultaneously.

Univariate analyses of the input data reveal their impact and sensitivity on the SPM. Results show that the changes in SPM value with respect to changes in the input data were consistent with reported trends in the literature.

The proposed framework for SPM is a significant first step in quantifying sustainability of built environment. However, further developments of the model are still required particularly in the following areas:

- Use of larger dataset to allow for higher order interactions
- Comprehensive parametric study to evaluate the range and predictability of the SPM model
- Enhance the input and measurable impacts for all three dimensions of sustainability
- Evaluate the generalized framework using different types of building and structure

6. Acknowledgements

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Chapter 4 – Sustainability performance metric application to Canadian single-family housing

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Sustainability, Housing, Design, Sustainability Performance Metric (SPM), LEED, Optimization

Abstract

Sustainability Performance Metric (SPM) framework developed by Marjaba et al. (2019) provides quantifiable and balanced measures of sustainability of built environment. This study compares SPM with LEED BD&C for Homes qualitatively and quantitatively. Moreover, the practicality and effectiveness of SPM in quantifying sustainability were examined using two case studies. The 1st case study simulates a trial and error decision making process when designing a new detached single-family house. The 2nd case study leverages the linear nature of the model underpinning the SPM to mathematically determine the optimum design. Univariate consideration of indicators is found to be counterproductive, whereas the multivariate SPM provides a balance between the indictors while determining the optimum design. Minimizing the energy consumption during occupancy alone resulted in a poor performance for all three dimensions of sustainability, leading to the conclusion that the likelihood of achieving a sustainable design without a holistic metric such as the SPM is low. The optimal designs were calculated to have an SPM of 0.36 to 0.38, where a practical selection of design parameters has an average SPM of 0.99, demonstrating the potential for improvement. The SPM framework demonstrates that linking and balancing all three dimensions of sustainability is paramount.

1. Introduction

A literature review and subsequent analyses have revealed the need for a scientific and quantitative sustainability measure of built environment [1], [2]. Accordingly, a Sustainability Performance Metric (SPM) framework was developed as a holistic model for quantifying sustainability of built environment [2]. The premise of the new development is that sustainability is three dimensional, economic, social and ecological, and that all dimensions are equally weighted and coupled. SPM comprises of two silos, input sustainability indicators requirements and observed variables quantified throughout the life cycle of the building, which are linked ideologically by objective and function statements set as a-priori and mathematically by the projection to latent structure (PLS) statistical method [3], [4]. Figure 1 illustrates the conceptual development of SPM.

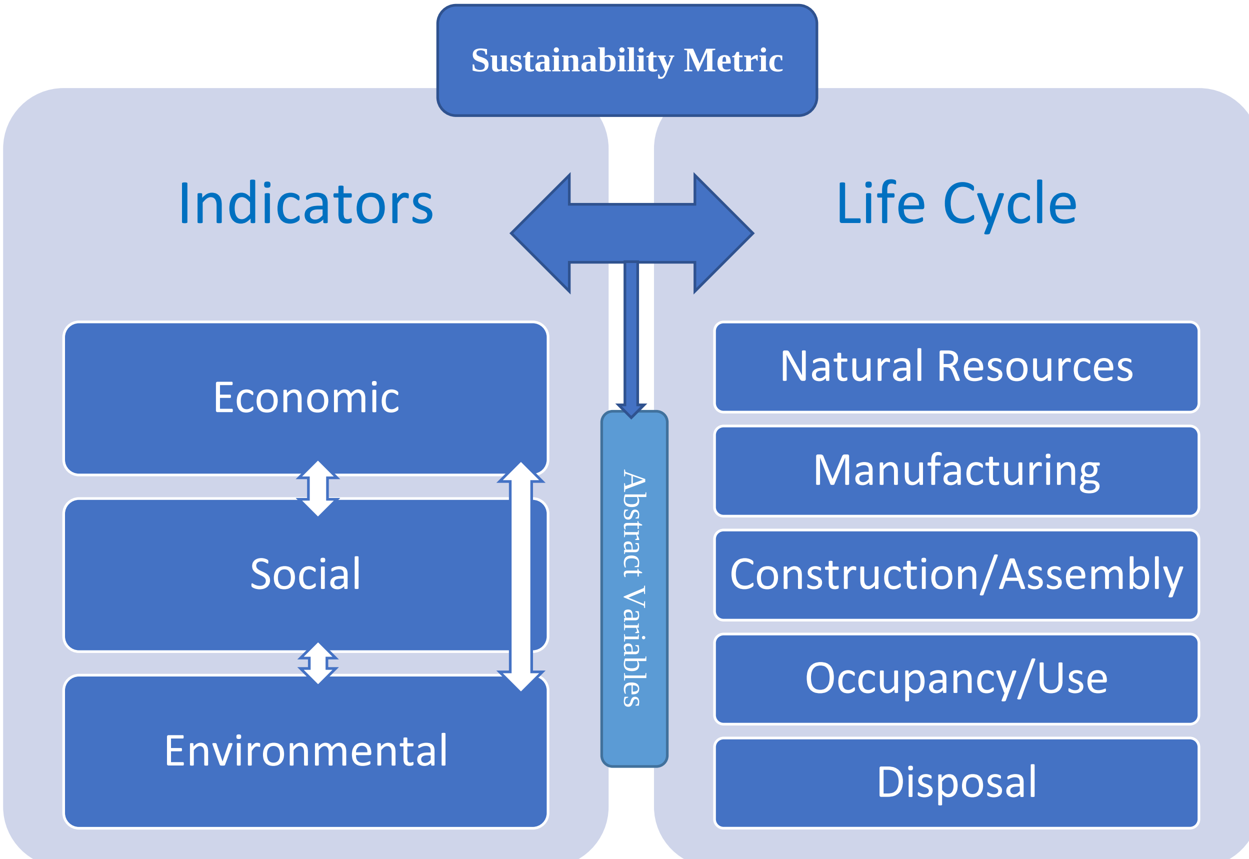

Figure 1. Conceptual representation of the sustainability framework metric [2].

Reliable models, specifically Athena Impact Estimator for Buildings [5], EnergyPlus [6], Building Information Modelling software, and an Input/Output socio-economic predictor [7], [8], which formed part of the SPM, were employed to generate the datasets. As a proof of concept, the use and versatility of the proposed SPM framework was demonstrated using single-family detached housing [2]. SPM yields a quantitative value that is scaled and standardized. Accordingly, a value of 1 implies the average and a value of zero the idealized target. Moreover, a low and a high-performance design are set to correspond to 1 standard deviation above and below the average with corresponding values of 1.67 and 0.33, respectively.

This study comprises of two parts: Part 1 consists of a comparative analysis to investigate the strengths and weaknesses of LEED BD&C Homes (Leadership in Energy and Environmental Design) [9] and SPM as metrics for sustainability; and Part 2 provides case studies to demonstrate SPM quantitative measure of sustainability. LEED, being the most widely used green building rating system in the world, is selected for the comparative analysis. Five cases, demonstrating the use of the SPM in the design of sustainable houses, are presented for which a LEED score is calculated. The two case studies correspond to the design of a new house by trial and error and the optimal design of a new house.

2. LEED and SPM as Sustainability Metrics

A review of sustainability/green building certification systems did reveal that they are not comprehensive and that the impact of sustainability's three dimensions, social, ecological and economy, are not adequately balanced, equally weighted and coupled [1]. In support of this finding, a comparative analysis between LEED BD&C Home credits and SPM observed variables quantified throughout the life cycle of the building is carried out. First, the LEED BD&C Home credits are divided into 3 categories for the purposes of this study: Procedural, Prescriptive and Performance. Subsequently, the main sustainability indicators are discussed from the 3 categories perspective.

1. **Procedural**: Procedural credits are those whose requirements are simply to follow a certain procedure. For this analysis, 6 procedural credits in LEED BD&C for Homes were identified: Integrative Process, Durability Management, Durability Management Verification, Preliminary Rating, Innovation, and LEED Accredited Professional.
2. **Prescriptive**: A prescriptive requirement is defined as a credit that is not a direct measure of the sustainability indicator, but rather a measure of an input factor or design parameter that is assumed to have a particular effect on a sustainability indicator. In LEED BD&C for Homes, 54 of the 64 credits are prescriptive requirements.
3. **Performance**: The remaining 4 credits are the performance credits. Those are Total Water Use, Minimum Energy Performance, Annual Energy Use, and Construction Waste Management. Those measures are assumed to be performance credits since they use direct measurement of a sustainability indicator, however the intent as described in the guiding document was not always consistent with this definition.

Energy Consumption and Global Warming Potential - Measuring the energy consumption, usually via detailed building simulations, is a performance requirement in which energy is a resource that needs to be conserved [10]–[12]. SPM treats energy as a resource. However, LEED's intent is to curb energy consumption as well as greenhouse gas (GHG) emission. For the latter to be considered a performance credit, emissions from energy consumption should be part of the metric. For this analysis, it is considered a performance credit to allow for a comparison with SPM.

As for Global Warming Potential (GWP), a common intent in LEED is to reduce emissions, which is captured via a multitude of prescriptive and procedural credits. On the other hand, SPM quantifies the eCO_2 that would be emitted into the atmosphere as a result of the design or decision, throughout the lifecycle of the structure. SPM yields a direct measure of the sustainability indicator.

Human Health - For factors impacting human health, both physical and mental, LEED uses prescriptive and procedural requirements that are assumed to increase the probability of resulting in better physical and mental health. The uncertainty or the variation in the probability of occurrences is much higher for these indicators. The SPM, using a similar number of inputs, uses the most current knowledge to scientifically quantify the impacts throughout the lifecycle. It should however be noted that the state of knowledge for this field is still at its infancy.

Economic and Social Wellness - LEED is mostly silent on economic and social indicators, with some prescriptive and procedural credits related to social wellbeing and equity. The SPM framework provides the scaffolding for applying more advanced performance metrics as is demonstrated in the prototype. Similar to the challenges facing human health indicators, the amount of data and/or models that are reliable and credible, are limited.

Innovation - Due to the mostly prescriptive scheme of LEED BD&C for Homes, LEED does not provide room for innovation in areas where the innovation is not prescribed. As a result, innovation credits have been provided, however they are themselves procedural and/or prescriptive. On the other hand, since SPM attempts to directly quantify the indicators, innovation is not hindered.

The following brief provides a critical summary of the two metrics:

- SPM measures the actual performance, regardless of the technology, design or innovation used to achieve the performance.
- SPM addresses the impracticality of measuring all indicators, for all phases of the life-cycle, for every possible option, by utilizing inputs comparable to LEED, and applying an in-built stochastic model to evaluate the indicators.
- SPM identifies lost opportunities and closes loopholes that may be present, to achieve a better performance.
- LEED provides a guide for the design features and is expected in most cases to result in a sustainable design.
- LEED and SPM should be thought of as complementary and not competing metrics. Conceptually, they aim to enhance sustainability, however, only SPM is developed to account equally for all three dimensions of sustainability as well as their coupling effect. Nonetheless, LEED provides practical ways to determine the input variables for sustainability.

For the case studies presented, several assumptions are needed to compare the LEED score and SPM value. The assumptions for the base house, summarized in Table 1, are meant to mitigate the differences between the two metrics by specifying the design criteria/conditions as a-priori. For reference, the LEED score per certification is: Certified - 40 to 49 points, Silver - 50 to 59 points, Gold - 60 to 79 points, and Platinum - 80 to 110 [9].

Table 1. Design assumptions and corresponding LEED points for the base House.

Category	Assumptions	Points	Max Points
INTEGRATIVE PROCESS (IP)			
Integrative Process	Assume that an integrative project team was assembled meeting the three required criteria (1 point) and a design charrette was conducted (1 point). The additional third option to train trades was not implemented (no points lost - this credit has a maximum of 2 points).	2	2
LOCATION AND TRANSPORATION (LT)			
LT Prerequisite: Floodplain Avoidance	Assume that the house is not developed with a flood hazard area or designated by the AHJ.	0	0
LT Credit: LEED for Neighborhood Development	Assume that the project is located within a certified LEED for Neighborhood Development.	15	15

LT Credit: Site Selection	Does not apply since LEED Neighborhood Development credit is used.	0	0
LT Credit: Compact Development	Does not apply since LEED Neighborhood Development credit is used.	0	0
LT Credit: Community Resources	Does not apply since LEED Neighborhood Development credit is used.	0	0
LT Credit: Access to Transit	Does not apply since LEED Neighborhood Development credit is used.	0	0
SUSTAINABLE SITES (SS)			
SS Prerequisite: Construction Activity Pollution Prevention	Assume that disturbed topsoil is stockpiled for reuse, the runoff is controlled, the swales are used to divert surface water from hillsides, and soils in areas with a slope greater than 15% is stabilized, and air pollution from dust is "prevented", and the site is less than 1 acre.	0	0
SS Prerequisite: No Invasive Plants	Assume that no invasive plant species and introduced into the landscape.	0	0
SS Credit: Heat Island Reduction	Assume the percentage of areas with shading and non-absorptive materials is 50-75%, which awards 1 point. If we had an area > 75%, then it would award 2 points.	1	2
SS Credit: Rainwater Management	Assume that 65-79% is a permeable area as a percentage of total area which awards 2 points. There are many other ways to get 1, 2, or 3 points.	2	3
SS Credit: Nontoxic Pest Control	There are several prescriptive measures to obtain up to 2 points. Assume non are awarded here.	0	2
WATER EFFICIENCY (WE)			
WE Prerequisite: Water Metering	Assume that a whole-house water meter is installed.	0	0
WE Credit: Total Water Use	Assume that the total indoor and outdoor water consumption is reduced by at least 30% over standard practice (assume this is done using blow flow toilets and fixtures and demand control outdoor water use). This awards 5 points. There are 12 points available for 65% reduction. These 5 points are ignored in the favour of 6 points available in the next credit.	0	0
WE Credit: Indoor Water Use	Fixtures are installed in accordance with this credit's requirements for the max 6 points.	6	6
WE Credit: Outdoor Water Use	Not attempted since no exterior landscaping or outdoor use of water is controlled.	0	6

	ENERGY AND ATMOSPHERE (EA)		
EA Prerequisite: Minimum Energy Performance	Assume the project meets the ENERGY STAR for Homes requirements, one of the refrigerators, dishwasher, or washing machine meet ENERGY STAR, and all duct runs are fully ducted.	0	0
EA Prerequisite: Energy Metering	Assume whole-house electric and gas meters are installed.	0	0
EA Prerequisite: Education of Homeowner, Tenant, or Building Manager	Assume and operations and maintenance manual is provided, and a 1-hour walkthrough is conducted as per the credit's requirements.	0	0
EA Credit: Annual Energy Use	Assume that the reference house annual energy consumption is calculated to be 49840 kWh/year. Assume that this is the annual energy consumption simulated for the Base House in Section 3.	0	29
EA Credit: Efficient Hot Water Distribution System	It can be assumed that the maximum hot water pipe length is 43 ft (for 1/2in pipes) for a water heater with no circulation loop or heat traced pipe, which would provide 2 points. However, it is assumed that a hot water test using EPA WaterSense testing verified that no more than 1.9 litres of water is stored in any piping between the water heater and fixture. This awards 3 points. It is also assumed that no pipe insulation is installed, which foregoes 2 points.	3	5
EA Credit: Advanced Utility Tracking	Assume that an hourly energy monitoring system is installed and the data is reported.	2	2
EA Credit: Active Solar-Ready Design	Assume no PV is installed and there are no PV-ready provisions.	0	1
EA Credit: HVAC Start-Up Credentialing	Assume no commissioning is undertaken.	0	1
	PRESCRIPTIVE PATH		
EA Credit: Efficient Hot Water Distribution System	Assume that the "performance path" is taken here	0	
EA Credit: Solar-Ready Design	Assume that the "performance path" is taken here	0	
EA Credit: HVAC Start-Up Credentialing	Assume that the "performance path" is taken here	0	
EA Credit: Advanced Utility Tracking	Assume that the "performance path" is taken here	0	
EA Prerequisite: Home Size	Assume that the "performance path" is taken here	0	

EA Credit: Building Orientation for Passive Solar	Assume that the "performance path" is taken here	0	
EA Credit: Air Infiltration	Assume that the "performance path" is taken here	0	
EA Credit: Envelope Insulation	Assume that the "performance path" is taken here	0	
EA Credit: Windows	Assume that the "performance path" is taken here	0	
EA Credit: Space Heating and Cooling Equipment	Assume that the "performance path" is taken here	0	
EA Credit: Heating and Cooling Distribution Systems	Assume that the "performance path" is taken here	0	
EA Credit: Efficient Domestic Hot Water Equipment	Assume that the "performance path" is taken here	0	
EA Credit: Lighting	Assume that the "performance path" is taken here	0	
EA Credit: High-Efficiency Appliances	Assume that the "performance path" is taken here	0	
EA Credit: Renewable Energy	Assume that the "performance path" is taken here	0	
MATERIALS AND RESOURCES (MR)			
MR Prerequisite: Certified Tropical Wood	Assume non tropical, certified wood is used.	0	0
MR Prerequisite: Durability Management	Assume the water management system Builder's requirement checklist is met as per the credit's requirement.	0	0
MR Credit: Durability Management Verification	Assume that a verification team inspected and verified each measure in the Energy Star water management checklist.	1	1
MR Credit: Environmentally Preferable Products	Assume that at least 50% of framing, aggregate for foundation, and drywall are extracted, processed and manufactured with 160 km from the project site. Assume that there are no environmentally preferred products.	2	4
MR Credit: Construction Waste Management	Assume waste is reduced from the reference by 40% awarding 2 points.	2	3
MR Credit: Material-Efficient Framing	Assume regular framing techniques are used, no advanced framing. No points awarded.	0	2
INDOOR ENVIRONMENTAL QUALITY (EQ)			
EQ Prerequisite: Ventilation	Assume the ventilation meets all the requirements for local exhaust and whole house mechanical ventilation.	0	0

EQ Prerequisite: Combustion Venting	Assume that all combustion appliances are vented and hardwired CO monitors are installed on each floor.	0	0
EQ Prerequisite: Garage Pollutant Protection	Assume all air handling equipment and ductwork are outside the garage envelope, and the garage is tightly sealed from conditioned spaces.	0	0
EQ Prerequisite: Radon-Resistant Construction	Assume the site is not located in an area with Radon requirements	0	0
EQ Prerequisite: Air Filtering	Assume air filters with MERV 8 or higher are installed on all recirculating space conditioning systems as per ASHRAE 62.2.	0	0
EQ Prerequisite: Environmental Tobacco Smoke	Assume that no control is required since this is a single-family home.	0	0
EQ Prerequisite: Compartmentalization	Assume that no compartmentalization is required since this is a single-family home evaluation.	0	0
EQ Credit: Enhanced Ventilation	Assume an occupancy sensor is installed in every bathroom with a shower or tub, and that a balanced ventilation system is installed.	3	3
EQ Credit: Contaminant Control	Assume no walk-off mat were installed, but a shoe removal and storage space is installed. Assume a pre-occupancy flush is conducted. Assume no air-tightness test is conducted.	1	2
EQ Credit: Balancing of Heating and Cooling Distribution Systems	Assume a single zone system (no credit), but with supply air-flow testing and pressure balancing.	2	3
EQ Credit: Enhanced Compartmentalization	Assume that no compartmentalization is required since this is a single-family home evaluation.	1	1
EQ Credit: Combustion Venting	Assume no fireplace or woodstove is installed.	2	2
EQ Credit: Enhanced Garage Pollutant Protection	Assume an exhaust fan in the garage is installed.	1	2
EQ Credit: Low-Emitting Products	Assume the site applied interior paints and coatings, flooring, insulation, adhesives and sealants, meet the requirements of CA Section 01350. Also, assume the composite wood products meet the California Air Resources Board requirements.	3	3
EQ Credit: No Environmental Tobacco Smoke	Does not apply.	0	0

INNOVATION (IN)			
IN Prerequisite: Preliminary Rating	Assume a meeting took place to identify the targeted LEED level, the credits selected, and responsibility for each credit	0	0
IN Credit: Innovation	Assume none of the options and points were selected here.	0	5
IN Credit: LEED Accredited Professional	Assume a LEED AP is on the project team	1	1
REGIONAL PRIORITY (RP)			
RP Credit: Regional Priority	Assume 2 of the 4 regional credits are awarded here.	2	4
TOTAL		**52**	**110**

3. Design of a Single-Family House by Trial and Error

A luxury 2-storey house with a basement, shown schematically in Figure 2, has a floor area of 100 m^2, 4 occupants, and a clear wall height of 3.05 m. It is built with a 100-year service life in a city whose population is 6,000,000 and a climate consisting of 3721 Heating Degree Days and 237 Cooling Degree Days corresponding to a base temperature of 18°C. The initial design is derived from minimum-code requirements. The corresponding design specifics and properties are given in Table 2. The analysis yielded an SPM of 0.77 for the base house. Using a single upgrade at a time, specifically increasing the attic insulation from 0.142 $W/m^2.K$ (R40) to 0.114 $W/m^2.K$ (R50), increasing the wall insulation from 0.237 $W/m^2.K$ (R24) to 0.189 $W/m^2.K$ (R30), or increasing the window thermal performance from 1.8 $W/m^2.K$ (R3.2) to 1.2 $W/m^2.K$ (R5), the revised design yields an SPM of 0.81, 0.77, and 0.77 for each of the three options, respectively, as reported in Table 3. These results demonstrate that energy savings is an important upgrade, however it is not a complete measure of sustainability. For Option 1, the attic thermal insulation was increased by 25% by increasing the thickness of the mineral wool insulation. The calculated SPM yielded a 5% inferior sustainability performance. Closer examination of the output sustainability indicators through the life cycle of the house, given in Table 3, the followings are deduced: 1) the EUI is reduced by 16%; 2) All the other environmental indicators, global warming potential, acidification potential, etc., show an increase in their values, therefore negatively impacting sustainability; 3) All the socio-economic indicators, Initial Expenditures / Value-Added, Initial Expenditures /

Gross-Output, Initial Expenditures / Employment, etc., also show an increase in their values, therefore negatively impacting sustainability. This example clearly demonstrates the consequences of using energy savings and GHG emission during occupancy reductions as indicators of sustainability which would have resulted with an erroneous assessment. The model results show that despite a significant savings in energy consumption during occupancy, adding more mineral wool insulation material to the attic has more negative than positive impacts on sustainability.

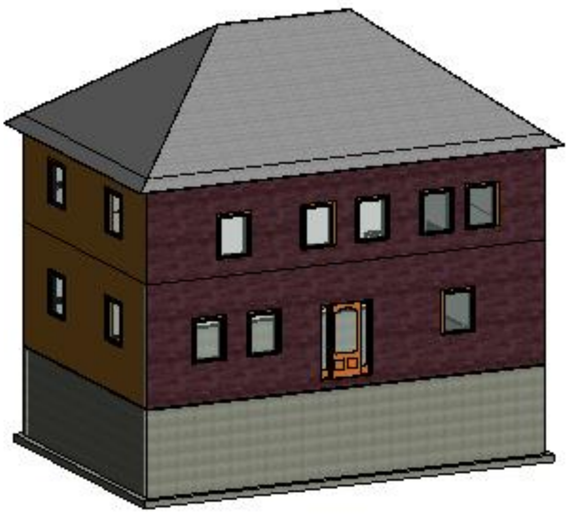

Figure 2. Schematic of the single-family house.

Option 2 was to increase the thickness of the mineral wool batt insulation. The outcome was a 3% reduction in EUI which was offset by the negative impact of all the other environmental indicators. The socioeconomic indicators were neutral. The negative impacts of increased costs were offset by the increase in salaries and economic output associated with higher costs. As such, SPM for Option 2 remained the same. Results of Options 3 and 4 yielded a modest improvement across all sustainability indicators which was not significant enough to be captured by SPM rounded to 2 significant figures.

The results from this case study revealed that adding insulation materials or insulative properties in general will reduce the energy consumptions and GHG emissions during occupancy. However, the addition of any insulative material can improve the sustainability performance if and only if the material does not negatively impact the environmental and the socioeconomic indicators during its entire life cycle. These results confirm that the use of a single measurement/output to assess sustainability will lead in most of the cases to an erroneous conclusion.

The combination of insulation levels between windows, walls, roofs, and other envelope components is a necessary consideration when considering energy efficiency during occupancy, and that for each structure and combination, there is a point of diminishing returns, most often referred to in the economic context. In other analyses, the point of diminishing returns is emissions savings and/or carbon pricing relative to cost of adding more insulation or upgrading fenestrations. And in rare cases, the point of diminishing returns is the embodied carbon within the insulation material itself relative to the savings in emissions as a result of more energy efficient structures. The results reveal that these aspects are important when considering sustainability but whether individually or collectively, these indicators are not sufficient, as a sustainability measure needs to account for environmental, social and economic factors and that their impacts have to be equally weighted. For example, the impact of factors such as job creation relative to adding more insulation, taxes, economic movement, etc., needs to be included as per the SPM framework. As illustrated in the second option, the SPM can be used to identify the point of diminishing returns for sustainability.

Table 2. Input data to various design options.

	Base House	**Option 1: Increase Attic Insulation**	**Option 2: Increase Wall Insulation**	**Option 3: Increase Window Thermal Resistance**	**Option 4: Improve Air Tightness**
Luxury Level	3	3	3	3	3
Percentage Brick Façade	25.00	25.00	25.00	25.00	25.00
Percentage EIFS Façade	0.00	0.00	0.00	0.00	0.00
Percentage Siding Façade	75.00	75.00	75.00	75.00	75.00
Percentage Stone Façade	0.00	0.00	0.00	0.00	0.00
Occupancy Time	16	16	16	16	16
Surrounding Area Percentage Brick Façade	25.00	25.00	25.00	25.00	25.00

Surrounding Area Percentage EIFS Façade	0.00	0.00	0.00	0.00	0.00
Surrounding Area Percentage Siding Façade	75.00	75.00	75.00	75.00	75.00
Surrounding Area Percentage Stone Façade	0.00	0.00	0.00	0.00	0.00
Total area of windows on all facades (m^2)	50.00	50.00	50.00	50.00	50.00
Percentage of facade facing south (%)	20.00	20.00	20.00	20.00	20.00
South Façade Area (m^2)	50.00	50.00	50.00	50.00	50.00
Number of Low Flow Faucet Fixtures	2	2	2	2	2
Number of dual flush toilets	3	3	3	3	3
Number of low-flow shower/tub fixtures	2	2	2	2	2
Building area-to-lot-area ratio (coverage)	75	75	75	75	75
Overall Attic U-value (with film - W/ m^2.K)	0.1420	0.1136	0.1420	0.1420	0.1420
Overall Wall U-value (with film) W/ m^2.K)	0.2370	0.2370	0.1890	0.2370	0.2370
Area Wt. Avg. Window U-value	1.8000	1.8000	1.8000	1.2000	1.8000
Area Wt. Avg. Window SHGC	0.4000	0.4000	0.4000	0.4000	0.4000
Roof Solar Absorptance	0.50	0.50	0.50	0.50	0.50
Wall Solar Absorptance	0.50	0.50	0.50	0.50	0.50
Heat Recovery Efficiency (0% for no heat recovery)	90	90	90	90	90
Setbacks (Yes [1] / No [0])	0	0	0	0	0
Air Tightness (ACH @ ATM)	0.1300	0.1300	0.1300	0.1300	0.0750
Percentage of fresh air from controlled source	0	0	0	0	0
Wood Structural Material Volume (m^3)	84.77	84.77	84.77	84.77	84.77
Concrete Structural Material Volume (m^3)	218.34	218.34	218.34	218.34	218.34

Steel Structural Material Volume (m^3)	0.24	0.24	0.24	0.24	0.24
Percentage Material Sourced Locally [1 yes]	0	0	0	0	0
Percentage Material Manufactured Locally [1 yes].	0	0	0	0	0
Percentage Material Assembled Locally [1 yes]	1	1	1	1	1
Percentage Prefabricated	0	0	0	0	0
Controlled Site Entrance and Exit	0	0	0	0	0
Review of Public Safety Performed	0	0	0	0	0
Review of Worker Safety Performed	0	0	0	0	0
Scaffolding and Protection Equipment	0	0	0	0	0
Construction QC in-place	0	0	0	0	0
Number of inspections by regulators	3	3	3	3	3
Number of inspections by professionals	1	1	1	1	1

Table 3. Output indicators to the various design options.

	Base House	**Option 1: Increase Attic Insulation**	**Option 2: Increase Wall Insulation**	**Option 3: Increase Window Thermal Resistance**	**Option 4: Improve Air Tightness**
Total Energy [kWh]	49,840	47,196	49,279	49,445	47,860
Energy Per Total Building Area [kWh/ m^2]	62	52	60	60	56
Global Warming Potential (kg CO_2 eq)	127,840	130,889	127,505	127,165	127,425
Acidification Potential (kg SO_2 eq)	817	840	818	813	816
HH Particulate (kg PM2.5 eq)	231	236	232	2294	231
Eutrophication Potential (kg N eq)	44	45	44	44	44

Ozone Depletion Potential (kg CFC-11 eq)	0.000849	0.000890	0.000857	0.000848	0.000852
Smog Potential (kg O_3 eq)	14,952	15,292	15,003	14,877	14,914
Total Primary Energy (MJ)	2,289,151	2,339,054	2,290,024	2,271,931	2,290,668
Non-Renewable Energy (MJ)	2,124,791	2,173,064	2,122,636	2,108,467	2,126,657
Fossil Fuel Consumption (MJ)	1,941,252	1,985,445	1,942,266	1,925,489	1,943,736
Initial Expenditures / Value-Added	0.2482	0.2729	0.2482	0.2482	0.2511
Initial Expenditures / Gross-Output	0.0889	0.0978	0.0889	0.0889	0.0900
Initial Expenditures / Salary	0.3669	0.4019	0.3657	0.3678	0.3707
Initial Expenditures / Employment ($/1 FTE)	17,500	19,275	17,447	17,546	17,690
Initial Expenditures / Taxes	0.5749	0.6298	0.5731	0.5763	0.5808
Initial Expenditures / Imports	0.6000	0.6573	0.5981	0.6015	0.6061
Annual Water Consumption (kL/year)	414	419	415	415	416
SPM value	***0.77***	***0.81***	***0.77***	***0.77***	***0.77***
LEED BD&C for Homes Score	***52 (Silver)***	***57 (Silver)***	***53 (Silver)***	***53 (Silver)***	***56 (Silver)***

Finally, observing the variations in the LEED scores, the improved energy savings achieved by air tightness is captured by both LEED and SPM. However, SPM also captured the fact that improving air tightness has, on the balance, reduced environmental, social and economic impacts over adding attic insulation. This is an example of a loophole that is not captured by LEED.

Of interest is the comparison of SPM values to the LEED scores. The results, given in Table 3, show that the trend in general is not the same for the two metrics. A detail examination of the results of Option 3 and 4 reveals that SPM values did not change whereas the LEED scores show an improvement. For Option 1, LEED scores indicates a better performance whereas SPM yields a worse performance. From a grouping perspective, the two metrics yielded the same sustainability output for this case study, but these results should not be construed as the same.

4. Optimum Design of a Single-Family House

Optimum design, being for total sustainability or energy consumption during occupancy, is always sought for buildings but rarely achieved in practice due to the traditional iterative approach. Results of the first case study demonstrate that intuitive and iterative approach does not lead necessary to an optimum design for sustainability. SPM, a mathematically formulated holistic model, affords the determination of a global optimum design for sustainability. The optimization in this case refers to minimizing the SPM value by minimizing the sustainability indicators within the SPM. The design requirements form the constraints or targets for the optimization problems (e.g. location). The design decisions that need to be made by the designer form the optimization variables. Based on this setup, the optimization problem then provides the designer with the optimal combination of variables or design parameters that result in the lowest possible of all sustainability indicators, approximating the combination that yields the lowest SPM for the known design requirements specified. Linear programming is used to determine the optimum design. Four optimization scenarios are considered by varying the objective function and targets to demonstrate SPM's ability to capture the optimum design for sustainability. The four scenarios are described in Table 4.

The optimization algorithm includes an SPE and Hotelling's T^2 limit [13] to ensure that the error of prediction is minimized and the optimal solution remains within the global limits set for the model. As a result, the optimization algorithm is set not to rigidly enforce the selected targets if they negatively impact the optimum design. The optimal solution for each scenario is calculated and shown in Table 4, however that is the mathematical solution which includes several deviations from known values as discussed. Informed by the optimization results, the designer would select more practical parameters as shown in Table 4. This should be used as a starting point for further refinement of the design. Table 5 gives the model outputs employed to calculate the SPM for each scenario as well as for the selected design parameters.

Table 4. Constraints of the optimization problem for each input.

	Targets	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Selected Design Parameters**
Objective Function (Minimize)	-	Minimize All Indicators	Minimize All Indicators except Energy Per Total Building Area	Minimize All Indicators except Energy Per Total Building Area	Minimize All Indicators	Parameters Selected Based on Project Constraints
Area Constrained Applied (Yes/No)	-	Yes	Yes	No	No	
Floor Footprint Area (m^2)	150	235	231	276	283	150
Number of Stories	2	2	2	2	2	2
Number of Occupants	4	5	5	5	5	6
Clear Wall Height (m)	2.44-3.05	2.88	2.87	2.88	2.88	2.74
Number of Basements	1	1	1	1	1	1
Luxury Level	5	6	6	6	6	6
Percentage Brick Façade	0 – 25	25	25	25	25	25
Percentage EIFS Façade	0 – 100	34	34	36	36	36
Percentage Siding Façade	0 – 100	25	25	25	25	25
Percentage Stone Façade	0 – 25	16	16	14	14	14
Occupancy Time	16	15	15	15	15	16
Service Life	100	49	45	45	48	90
HDD18	3,721	4,705	4,968	5,257	5,023	3,721
CDD18	237	1,247	1,206	1,005	1,034	237

Population	5,928,040	1,389,104	1,288,215	1,591,532	1,701,916	6,000,000
Surrounding Area Percentage Brick Façade	25	20	20	24	24	25
Surrounding Area Percentage EIFS Façade	0	18	17	14	15	0
Surrounding Area Percentage Siding Façade	75	26	26	24	23	75
Surrounding Area Percentage Stone Façade	0	36	36	38	37	0
Total area of windows on all facades (m^2)	40 – 50	42.9	43.3	41.5	41.1	35
Percentage of facade facing south (%)	17 – 20	27	27	27	27	20
South Façade Area (m^2)	40 – 80	80	80	80	80	80
Number of Low Flow Faucet Fixtures	2	3	3	4	4	2
Number of dual flush toilets	3	2	2	2	2	3
Number of low-flow shower/tub fixtures	2	1	1	2	2	2
Building area-to-lot-area ratio (coverage)	75	39	40	40	40	75
Overall Attic U-value (with film - $W/ m^2.K$)	> 0.185 (< R31)	0.243	0.244	0.245	0.244	0.244
Overall Wall U-value (with film) $W/ m^2.K$)	> 0.154 (< R37)	0.230	0.232	0.235	0.234	0.234
Area Wt. Avg. Window U-value ($W/ m^2.K$)	> 1.25	2.63	2.626	2.776	2.787	2.79

Area Wt. Avg. Window SHGC	0.2 – 0.8	0.515	0.513	0.511	0.512	0.512
Roof Solar Absorptance	0.25 – 0.95	0.519	0.515	0.516	0.520	0.52
Wall Solar Absorptance	0.25 – 0.95	0.633	0.631	0.626	0.627	0.625
Heat Recovery Efficiency (0% for none)	90	47	47	45	45	90
Setbacks (Yes [1] / No [0])	0	1	1	1	1	0
Air Tightness (ACH @ ATM)	0.1 – 0.3	0.3	0.3	0.3	0.3	0.3
Percentage of fresh air from controlled source	None	42	42	40	40	0
Wood Structural Material Volume (m^3)	None	50.03	49.24	55.65	56.63	57
Concrete Structural Material Volume (m^3)	None	126.44	119.39	131.54	139.01	125
Steel Structural Material Volume (m^3)	None	0.524	0.49	0.60	0.64	0
Percentage Material Sourced Locally [1 yes]	None	1	1	0	0	0
Percentage Material Manufactured Locally [1 yes]	None	0	0	0	0	1
Percentage Material Assembled Locally [1 yes]	None	1	0	1	1	1
Percentage Prefabricated	None	0.00	0.00	0.00	0.00	0
Controlled Site Entrance and Exit	None	1	1	1	1	1
Review of Public Safety Performed	None	1	1	1	1	1

Review of Worker Safety Performed	None	1	1	1	1	1
Scaffolding and Protection Equipment	None	0	0	0	0	0
Construction QC in-place	None	1	1	1	1	1
Number of inspections by regulators	None	6	6	6	6	6
Number of inspections by professionals	None	5	5	5	5	5

Table 5. Optimization results, practical interpretations, and associated SPMs.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Selected Design Parameters**
Total Energy [kWh]	48,451	48,499	54,808	55,121	65,142
Energy Per Total Building Area [kWh/m^2]	117	125	113	104	127
Global Warming Potential (kg CO2 eq.)	86,998	81,577	87,264	92,912	96,095
Acidification Potential (kg SO2 eq.)	529	496	519	553	599
HH Particulate (kg PM2.5 eq.)	142	133	143	152	179
Eutrophication Potential (kg N eq.)	29	27	28	30	33
Ozone Depletion Potential (kg CFC-11 eq.)	0.000566	0.000536	0.000515	0.000542	0.000596
Smog Potential (kg O_3 eq.)	9,418	8,818	9,353	9,966	10,639
Total Primary Energy (MJ)	1,440,089	1,341,471	1,492,785	1,598,098	1,757,587
Non-Renewable Energy (MJ)	1,331,672	1,236,097	1,372,881	1,474,622	1,616,147
Fossil Fuel Consumption (MJ)	1,203,219	1,118,176	1,234,618	1,324,813	1,460,815
Initial Expenditures / Value Added	0.0389	0.0365	0.0322	0.0342	0.4518
Initial Expenditures / Gross Output	0.0140	0.0131	0.0116	0.0123	0.1619

Initial Expenditures / Salary	0.0698	0.0678	0.0619	0.0632	0.7032
Initial Expenditures / Employment ($/1 FTE)	2,606	2,509	2,194	2,256	34,302
Initial Expenditures / Taxes	0.109	0.106	0.097	0.099	1.102
Initial Expenditures / Imports	0.114	0.110	0.101	0.103	1.150
Annual Water Consumption (kL/year)	373	373	365	366	493
SPM	***0.37***	***0.36***	***0.37***	***0.38***	***0.99***

A review of the results in Tables 4 and 5 reveals the commonalities between the optimal solutions for the various scenarios and provides confidence in the target values entered. An optimal SPM value of 0.36-0.38 is the expected lower boundary for housing given today's building technologies. The results demonstrate SPM's strength in balancing the impacts of economic, ecological and social. This stems from the following observations:

1. Area of the house was increased to balance the impacts of all three dimensions. Increased area provides a balance between negative environmental impact with positive economic and social impact.
2. Selected materials, properties and construction method provide a balance between economic, ecological and social impacts.
3. Total ecological impact does not correlate directly with the energy consumption during occupancy.
4. Impact of total energy throughout the house's life-cycle is more impactful on the environment than the energy consumption during occupancy.
5. Recommended design area ranged between 230 and 280 m^2 depending on whether the area is constrained in the model or not. Balancing the impacts and the scope of the model parameters overrides the set constraints for these scenarios.
6. First 4 scenarios yielded the same SPM values which demonstrate the model ability to yield designs that meets the requirements set for sustainability.
7. Restricting the design values to those selected by the designer yielded a design with an average sustainability performance.

8. Iterative approach to designing a house that meets sustainability requirements, will seldom lead to the optimum design without the use of an optimization approach that balances the impacts equally among all three dimensions.

The strength of the proposed SPM framework is significantly amplified when combined with linear programming to identify the optimum sustainability design. Designers can use the metric to establish an initial design and to check the overall sustainability of the final design. Regulators can use it to quantify the impact of policies on all three dimensions of sustainability. In brief, the implementation of SPM is limited by the availability of data. The SPM framework is applicable to all built environment.

5. Conclusions

In conclusion, the utility of the SPM is demonstrated through a review of LEED relative to the SPM from a qualitative and quantitative perspective, and two case studies. The SPM was used in the hypothetical design of a single-family detached house using trial and error and optimization. The findings are summarized as follow:

1. Univariate consideration of individual sustainability indicators will lead to counterproductive designs.
2. A holistic design tool such as the SPM that considers all sustainability indictors needs to be a requirement when determining the various points of diminishing returns.
3. SPM, which is a holistic quantifiable metric for sustainability, does not produce the same trends as LEED, although the house LEED certificate corresponded to that of SPM.
4. Sustainability design must include all three dimensions, economic, social and ecological, they must be linked and equally weighted.
5. Iterative trial and error approach for minimizing energy consumption during occupancy will not for most designs lead to a house with higher sustainability.
6. Linear programming (optimization) built on top of the SPM results in a unique optimal design solution that balances all three dimensions of sustainability.

7. The optimization, although it is sensitive to the set targets, is strongly influenced by the balance of all three dimensions and the minimization of SPM.
8. Optimal single detached family house design has SPM of 0.36 to 0.38, indicating that sustainability requirements can be met with current building technologies.
9. The SPM demonstrated particular value in its direct and scientific link to all three dimensions of sustainable performance which was established via a data-driven approach capitalizing on the strengths of the PLS algorithm.

6. Acknowledgements

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Chapter 5 – Building Envelope Energy Efficiency Measure

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Abstract

Thermal properties of the building envelope (BE) prescribed by codes and standard do not provide a consistent and comprehensive measure of its performance. Qualitative comparative analysis employed by the codes to assess energy savings is deterrent to technology development as the potential energy savings are never realized. A new metric referred as the building envelope coefficient of performance (BECOP) is proposed which compares the BE performance to an ideal system. BECOP, which is invariant to the calculation methods and applicable to all building types and climate zones, is a comprehensive metric for assessing the thermal performance of building envelopes while accounting for the various building characteristics. The sensitivity and range of BECOP were assessed for the Canadian climate and construction methods. Using case studies, BECOP results revealed that current practices and regulations pertaining to the building envelope are inconsistent and fail to provide any measure of efficiency and that current building envelope technologies are not energy efficient. A maximum BECOP value of 35% is obtained for the best building envelope technology revealing the inefficiencies and energy saving potentials.

1. Introduction

The need to balance between growing global demands for energy and sustainability is paramount, however its realization is stunted by today's technologies, knowledge, and policies [1]-[3]. For reference, the built environment in Canada produced about 17% of greenhouse gases (GHG) emissions [4] with 14% attributed to existing residential buildings corresponding to 17% of all combined energy [5]. In contrast, $12 billion in energy saving were realized in Canada in 2013 through residential energy conservation measures [4]. These statistics are supported by an econometric multivariate analysis where inefficient thermal envelopes and heating systems have been identified as the dominant energy inefficiency problems in households [6].

Buildings' energy consumption depends on the climate, orientation, size, occupants, building envelope specifications, HVAC system specifications, lighting specifications, available controls, equipment, etc. [7]. Regulating buildings energy efficiencies in codes and standards, which is increasingly being sought [8]-[9], is starting to be recognized as one of the most cost-effective tools for achieving energy efficiency in buildings. In 2017, the Building Code of British Columbia (BCBC) prescribed the highest level of performance as the annual net zero energy (NZE) consumption during occupancy [10]. Towards this objective, the thermal energy demand intensity (TEDI) and mechanical energy use intensity (MEUI) are utilized to regulate the energy efficiency of buildings [10]. Examination of the two metrics' premise reveals that TEDI and MEUI are not compatible and that only MEUI has been standardized. The MEUI includes absolute measures of efficiency whereas the TEDI includes relative measures of thermal performance. Accordingly, the building envelope energy efficiency as an absolute measure is missing.

Typical metrics employed to assess buildings energy efficiency are through qualitative comparative analysis (QCA), where the causal effects of the building characteristics on the energy consumption are measured. The representative metrics include (1) energy consumption per unit time, usually annual totals [11]; (2) energy use intensity (EUI) [12]; (3) relative energy consumption or EUI, as opposed to absolute energy consumption or EUI [13]; (4) hybrid or combinations of the first three; and (5) other metrics mostly being calculated or deduced from regression type models [14]–[18]. Moreover, economic justifications, which have been an inherent rationale for the incremental changes in codes and standards, have been substantiated by QCA results. The implications have been detrimental to sustainability, being ecological and economical, and most critically, the inability to quantify the actual energy saving potentials has stunted the development of new and innovative energy efficient building envelope components and systems. This postulation is confirmed by findings of scientific studies reported in the literature:

1) A multi-objective optimization study was carried out to assess the EU prescribed cost-optimal approach of a balance of energy and economic targets [19]. The study showed that a zero-energy target is possible with current technology provided a lower indoor thermal comfort is allowed [19]. Accordingly, energy efficiencies of the current building envelope technologies are not adequate to meet zero-energy target.
2) Results of life cycle cost implications of energy efficiency measures in new residential buildings reveal that higher levels of energy efficiency requirements via building regulations are justified on the basis of both economic and environmental grounds [20]. Findings demonstrate that the current energy efficiency requirements, particularly for the building envelope, are too low for new residential buildings to meet sustainability requirements.

3) Results from net zero energy buildings (NZEB) study show that increasing the thermal energy efficiency of building envelope is a step towards fulfilling all of the NZEB balances [15]. Others have reported that increasing the building envelopes insulative properties is more economically and ecologically effective in colder climates and less effective in warmer climates depending on the internal heat loads [21]. Findings on NZEB, which agree with the previous studies' findings, confirm that the energy efficiency of the building envelope needs significant improvement and that the design requirements are climate dependent.
4) Review of building envelope components for passive buildings concluded that the additional cost of energy efficient building envelope can be recouped by the reduced size of mechanical systems [22]. The results confirm that improving the thermal resistance of the building envelope is both economically and ecologically viable.
5) Results from case studies conducted on a house located in Toronto Canada show that a 70% reduction in energy consumption of code minimum requirements by improving the building envelope's thermal properties is achievable with less than 7% increase in the construction budget [23].

In brief, the results from several scientific studies reveal with certainty that higher energy efficiencies for the building envelope are needed to meet the NZEB target and that the most cost-effective and ecologically sound house design is always more energy efficient than the current energy code requirements. Accordingly, this study was undertaken to review the progress of Canada's National Codes pertaining to the thermal performance of building envelopes for residential buildings with specific focus on housing, to discuss the implications of the codes on the development of new technologies, and to postulate a new metric for assessing the thermal efficiency of building envelopes. Case studies are then presented to demonstrate the range, sensitivity and applications of the proposed thermal efficiency metric for the building envelope.

2. Historical Development of Building Envelope Energy Efficiency Measures for Canadian Housing

2.1 Chronological Review

The National Building Code of Canada (NBC) first issued in 1941, is the model building code of Canada. Since 1960, NBC was revised every 5 years except for the change from prescriptive to objective-based codes between the 1995 and 2005 editions. Review of the NBC 1985 to 2010 pertaining to Housing and Small Buildings reveals that energy efficiency was not part of the code requirements. The prescribed requirements were for thermal insulation, air leakage and vapour barriers to prevent moisture condensation and to ensure comfortable conditions for the occupants [Article 9.26.2.1, [24]; Article 9.25 [25]]. In 2012 and through a special amendment for Part 9 of NBC, energy efficiency requirements were added to Section 9.36 in a 2012 Amendment [25]. "The Environment" was added as an NBC objective to mitigate the probability of harming the environment due to excessive use of energy [OE1.1] [25]. The corresponding minimum requirements aimed at energy efficiency were prescribed using three paths to compliance; prescriptive, trade-off, and performance. For the prescriptive path, the effective thermal resistances were specified for the building envelope and are reproduced in Tables 1 and 2 for reference.

Table 1a. Effective thermal resistance of above ground opaque assemblies in building without heat recovery ventilator [26].

Above-ground Opaque building Assembly	Heating Degree-Days of Building Location, in Celsius Degree-Days					
	Zone 4	Zone 5	Zone 6	Zone 7A	Zone 7B	Zone 8
	<3000	3000 to 3999	4000 to 4999	5000 to 5999	6000 to 6999	≥7000
	Minimum Effective Thermal Resistance (RSI), (m^2K)/W					
Ceiling below attics	6.91	8.67	8.67	10.43	10.43	10.43
Cathedral ceilings and flat roofs	4.67	4.67	4.67	5.02	5.02	5.02
Walls	2.78	3.08	3.08	3.08	3.85	3.85
Floors over unheated spaces	4.67	4.67	4.67	5.02	5.02	5.02

Table 1b. Effective thermal resistance of above ground opaque assemblies in building with heat recovery ventilator [26].

Above-ground Opaque building Assembly	Heating Degree-Days of Building Location, in Celsius Degree-Days					
	Zone 4	Zone 5	Zone 6	Zone 7A	Zone 7B	Zone 8
	<3000	3000 to 3999	4000 to 4999	5000 to 5999	6000 to 6999	≥7000
	Minimum Effective Thermal Resistance (RSI), (m^2.K)/W					
Ceiling below attics	6.91	6.91	8.67	8.67	10.43	10.43
Cathedral ceilings and flat roofs	4.67	4.67	4.67	5.02	5.02	5.02
Walls	2.78	2.97	2.97	2.97	3.08	3.08
Floors over unheated spaces	4.67	4.67	4.67	5.02	5.02	5.02

Table 2. Thermal conductance of fenestration and doors [26].

Components	Heating Degree-Days of Building Location, in Celsius Degree-Days					
	Zone 4	Zone 5	Zone 6	Zone 7A	Zone 7B	Zone 8
	<3000	3000 to 3999	4000 to 4999	5000 to 5999	6000 to 6999	≥7000
	Maximum U-value, W/(m^2.K), Minimum Energy Rating in Brackets (if available)					
Fenestration and doors	1.80 (21)	1.80 (21)	1.60 (25)	1.60 (25)	1.40 (29)	1.40 (29)
Skylights	2.90	2.90	2.70	2.70	2.40	2.40

The Model National Energy Code of Canada for Buildings, introduced in 1997 [27], was Canada's first national standard for building energy performance. It was updated in 2011 and renamed the National Energy Code of Canada for Buildings (NECB) [28] and further updated in 2015 and 2017 [29]-[30] to ensure a high level of energy efficiency in new Canadian buildings. An objective of NECB is energy efficient buildings with a focus on 5 key building elements: building envelope, lighting, HVAC, water heating, and electrical power systems and motors. Building envelope, which is the objective of this study, includes floors, walls, windows, doors and roofing, and air infiltration rates. Like the NBC, the NECB offers three compliance paths: prescriptive, trade-off and performance. The prescriptive requirements for the building envelope thermal properties are reproduced from 1970 to 2017 per climate zone for wall, roof, ground floor and window in Tables

3 to 6, respectively [28]-[32]. Comparing NBC 2015 Part 9 and NECB 2015 building envelope's thermal resistance requirements reveals that the latter prescribes higher energy efficiency requirements. Accordingly, NECB data are analysed to critically assess the code's approach vis-a-vie energy efficiency.

Table 3. Thermal conductance of wall (W/m^2.K).

Climate zone	1970		2007				2011	2015	2017
	Electric heating	Non-electric heating	Steel frame		Wood frame				
			Continuous Insulation	Cavity Insulation	Continuous Insulation	Cavity Insulation			
Zone 4	0.40	0.62	0.75	0.38	1.14	0.38	0.315	0.315	0.315
Zone 5	0.34	0.51	0.57	0.27	-	0.27	0.278	0.278	0.278
Zone 6	0.34	0.51	0.57	0.27	0.57	0.38	0.247	0.247	0.247
Zone 7A	0.34	0.51	0.57	0.27	0.57	0.27	0.210	0.210	0.210
Zone 7B	0.34	0.51	0.57	0.27	0.57	0.27	0.210	0.210	0.210
Zone 8	0.28	0.45	0.57	0.27	0.57	0.27	0.183	0.183	0.183

Table 4. Thermal conductance of roof (W/m^2.K).

Climate zone	1970		2007				2011	2015	2017
	Electric heating	Non-electric heating	Attic space		Without attic space				
			Wood frame	Steel frame	Wood frame	Steel frame			
Zone 4	0.51	0.68	0.19	0.19	0.26	0.26	0.227	0.227	0.193
Zone 5	0.45	0.62	0.13	0.13	0.22	0.19	0.183	0.183	0.156
Zone 6	0.45	0.62	0.12	0.12	0.15	0.15	0.183	0.183	0.156
Zone 7A	0.45	0.62	0.12	0.12	0.15	0.15	0.162	0.162	0.138
Zone 7B	0.45	0.62	0.12	0.12	0.15	0.15	0.227	0.162	0.138
Zone 8	0.45	0.57	0.11	0.11	0.15	0.15	0.183	0.142	0.121

Table 5. Thermal conductance of ground floor (W/m^2.K).

Climate zone	1970		2007		2011	2015	2017
	Heating source		Wood frame	Steel frame			
	Electric heating	Non-electric heating	Cavity Insulation				
Zone 4	0.51	0.68	0.27	0.15	0.227	0.227	0.227
Zone 5	0.45	0.62	0.23	0.15	0.183	0.183	0.183
Zone 6	0.45	0.62	0.23	0.15	0.183	0.183	0.183
Zone 7A	0.45	0.62	0.15	0.15	0.162	0.162	0.162
Zone 7B	0.45	0.62	0.15	0.15	0.162	0.162	0.162
Zone 8	0.45	0.57	0.15	0.15	0.142	0.142	0.142

Table 6. Thermal conductance of window (W/m^2.K).

Climate zone	2007	2011	2015	2017
Zone 4	2	2.4	2.4	2.1
Zone 5	2	2.2	2.2	1.9
Zone 6	2	2.2	2.2	1.9
Zone 7A	2	2.2	2.2	1.9
Zone 7B	2	2.2	2.2	1.9
Zone 8	2	2.6	1.6	1.4

2.2 Analytical Review of the Building Envelope Minimum Requirements

Historically, the progression of the building envelope thermal resistance requirements is through a percentage increase in the thermal resistance. Comparative analysis of the NECB wall properties shows that on average the thermal resistance was increased 72% and 29% for the year 2007 and 2011, and 0% thereafter. For the NECB roof properties requirement, the thermal resistance was increased 260%, -7%, 11% and 17% for the year 2007, 2011, 2015 and 2017, respectively. For the ground floor, the thermal resistance was increased 230% and 10% for the year 2007 and 2011, and 0% thereafter. As for the windows, the thermal resistance decreased on average by 13% for the 2011 edition, remained the same except for Zone 8 in the 2015 edition and then increased on average by 15% for the 2017 edition. Although the motivation is energy efficiency, the logic supporting the changes is not consistent and appears to be arbitrary. Normalized heat transfer rate through the building envelope, calculated according to Eq. 1, is employed to assess the impact of the thermal properties requirements on the building energy consumption.

$$\dot{q} = U.HDD_{Avg} \tag{1}$$

in which U and HDD_{Avg} are the conductance ($W/m^2.K$) and average heating degree days corresponding to the climate zone, respectively. HDD for Canadian climate are given in Table 7. The results, plotted in Figures 1 to 4 corresponding to wall, roof, ground floor and window, respectively, reveal that a) the heating energy is designed to increase with HDD, b) the heat transfer rate differs for the different building envelope systems, and c) the requirements which are incremental hardly changed for the past 10 years. Accordingly, and focusing solely on the building envelope, NECB requirements are designed to accept higher heating energy with increased HDD which is counter intuitive from an economic and ecological perspective. Moreover, NECB assesses improvements through comparison with the preceding thermal resistance requirements. This methodology which is adopted by most if not all codes, although it is sound mathematically, it is misleading as it measures improvements with the worst case and not the best or perfect case, and is deterrent to technology development as the potential energy savings are never realized. As such, a consistent and comprehensive metric for measuring the energy performance of the building envelope is needed.

Table 7. Heating degree days for Canadian climate zones.

Zone	HDD below 18°C	HDD_{Avg}
4	< 3000	3000
5	3000-3999	3500
6	4000-4999	4500
7A	5000-5999	5500
7B	6000-6999	6500
8	≥ 7000	8000

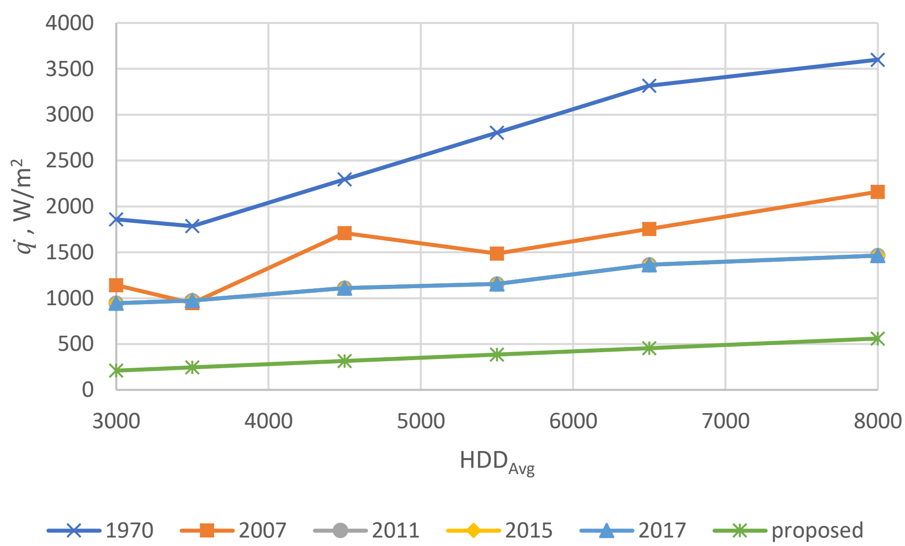

Figure 1. Normalized heat transfer through the walls per code specified properties.

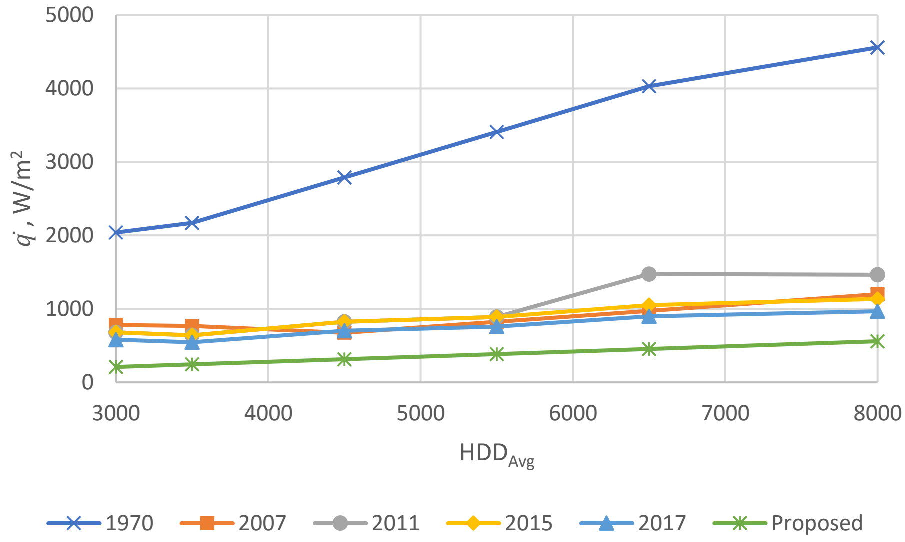

Figure 2. Normalized heat transfer through the roof per code specified properties.

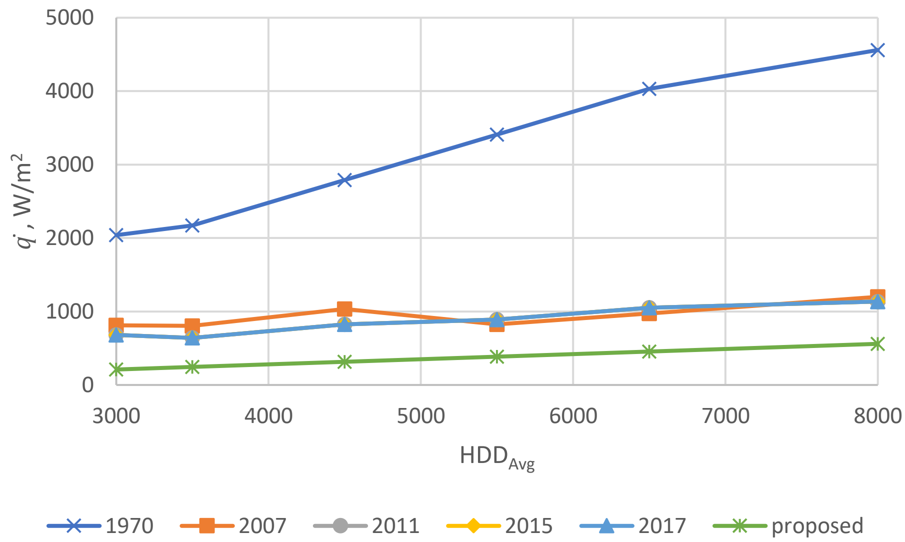

Figure 3. Normalized heat transfer through the ground floor per code specified properties.

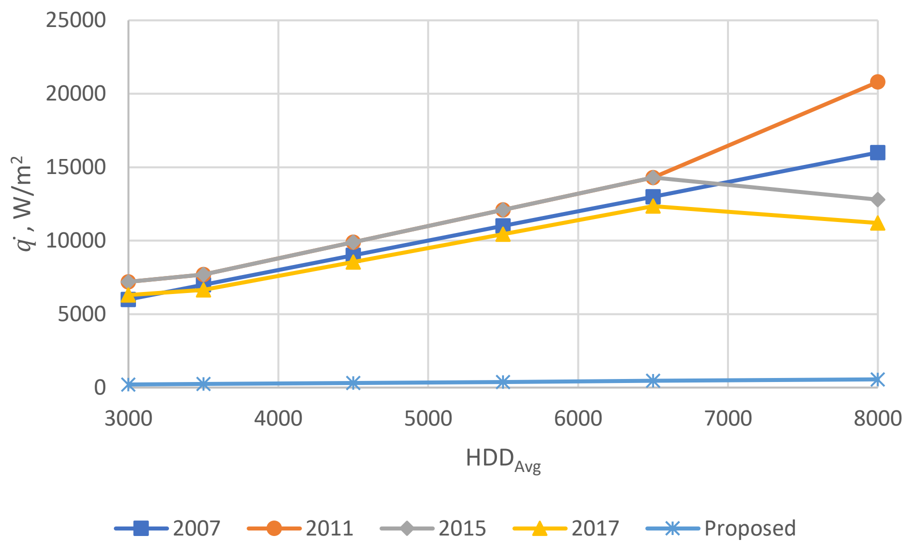

Figure 4. Normalized heat transfer through the windows per code specified properties.

3. Building Envelope Energy Efficiency Measure

Building energy efficiency metrics are assessment measures prescribed to compare the buildings energy consumption. For metrics that include mechanical equipment energy consumption, they include datums in the form of equipment efficiencies and COP that are standardized and embedded in the assessment measures. These datums ensure that the assessment employs the same yardstick and consistency for all equipment and systems. Whereas for metrics specifically designed for capturing the building envelope performance, the datums resemble more of moving averages in the form of compliance targets, which render the metrics inconsistent and irregular. To overcome this deficiency, an efficiency measure analogous to the mechanical equipment is adapted by postulating a "perfect" building envelope system as a datum. A "perfect" thermal insulating medium which has a zero-thermal transmittance, would be ideal for this application except that a zero value for thermal property is mathematically problematic in energy modelling. Accordingly, an equivalent "ideal" system for the building envelope is proposed that comprises of following properties:

- Thermal conductance: 7.0×10^{-2} W/m^2.K
- Thermal diffusivity: 1.05×10^{-5} m^2/h

- Absorptance: 0.2
- Air leakage: 0.1 ACH at atmospheric pressure

The proposed "ideal" building envelope system provides a datum for assessing the thermal performance, similar or analogous to the COP of equipment, and to be used as the ideal building envelope (walls, roof, slabs, windows and doors). As such, this metric is referred to as the Building Envelope Coefficient of Performance (BECOP), where

$$BECOP = \frac{q_{Ideal}}{q_{BE}}$$

In which q_{Ideal} and q_{BE} are the heat losses through the building envelope while employing the ideal system and the subject building, respectively. BECOP provides a consistent and relative measure of the building envelope thermal performance while keeping all other building variables the same. The metric is independent of the calculation method, being energy modelling tools, hand calculations or any other statistical or hybrid tools, and requires that the same analysis method be used throughout. The proposed BECOP is applicable to all building types and Climate Zones, and is designed to provide a measure that is compatible and comparable to existing systems within the building such as HVAC, lighting, etc. Accordingly, the energy saving potential of the building envelope shifts from passive to active approach where large energy savings can be realized [22]. In this study, the energy modelling tool EnergyPlus [33] is used to demonstrate the applicability, versatility and sensitivity of BECOP.

3.1 Range of BECOP

The range of BECOP for Canada is gauged by employing extreme Climate Zones 4 and 8 along with three levels of design specifications of the building envelope thermal performance, referred to as "low", "typical" and "high" thermally efficient relative to North American construction practices. The corresponding building characteristics and envelope properties are given in Tables 8 and 9. The building is a detached single-family house, 2-storeys high with a basement, rectangular in shape, and long face oriented in the E-W direction (90° to North), and has the same window areas on all four sides. The plug loads, lighting loads, occupancy loads, domestic hot water load, etc., and their respective schedules are taken from the National Building Code of Canada Section 9.36 [24] and/or the National Energy Code for Buildings [30] and are given in Table 10.

The thermal properties are derived from current codes, past codes, and expected future codes. The past codes represent older and low energy efficient construction practices, and the expected future codes represent anticipated future technologies and construction practices with higher energy efficiency, as compiled in Tables 8 and 9. The results, presented in Tables 11 and 12, show the energy consumption due to heat loss through the building envelope for the three archetypes and two climate zones. Abbotsford, BC and Iqaluit, NU represent Climate Zones 4 and 8, respectively. First review of the BECOP reveals the extreme inefficiency of the building envelope from an energy perspective where the best BECOP is below 35% compared to above 90% for furnaces and other electrical equipment. For low performance building envelopes, the calculated BECOP for Zone 4 is 0.1% and 4.0% for Zone 8. For the typical construction, the BECOP for Zone 4 is 0.2% and 9.2% for Zone 8. For the high-performance envelope, the BECOP for Zone 4 is 0.7% and 32.2% for Zone 8. These values indicate that the current BECOP ranges between 0.1% and 35%. A BECOP of 100% implies that the building envelope thermal performance is equivalent to that of the idealized building envelope.

Closer examination of the BECOP values reveals that the metric is capturing the coupled effect of the thermal resistance, Climate Zone and internal heat gains. With the latter being constant, as the HDD increases, the impact of an efficient building envelope is captured and reflected with an increase in BECOP value. Moreover, the significance is most visible for the high-performance construction where the BECOP value goes from less than 1% to 33%. If the values are compared across the levels of construction, a clear upward trend is observed from Figure 5. For Zone 8, the impact of the building envelope properties on the BECOP is significant with the value increasing exponentially to 33%.

Table 8. Properties and characteristics of a house located in Abbotsford, BC (Zone 4).

	Building Envelope Thermal Efficiency		
	Low	Typical	High
HDD18	2,920	2,920	2,920
CDD18	74	74	74
Floor Footprint Area (m^2)	118.45	118.45	118.45
Aspect Ratio	1.5	1.5	1.5
Window-to-wall Ratio	60%	40%	20%
Wall Height (m)	2.74	2.74	2.74
Overall Wall U-value ($W/m^2.K$) [R-value]	0.32 [R18]	0.159 [R36]	0.103 [R55]
Attic U-value ($W/m^2.K$) [R-value]	0.189 [R30]	0.095 [R60]	0.072 [R79]
Foundation Wall Overall U-value ($W/m^2.K$) [R-value]	0.322 [R18]	0.169 [R34]	0.172 [R33]
Area Weighted Average Window U-value ($W/m^2.K$)	3.166 [R1.8]	1.704 [R3.3]	0.836 [R6.8]
Area Weighted Average Window SHGC	0.493	0.267	0.25
Air Tightness (ACH at atm)	0.75	0.35	0.1

Table 9. Properties and characteristics of a house located in Iqaluit, NU (Zone 8).

	Building Envelope Thermal Efficiency		
	Low	Typical	High
HDD18	9,924	9,924	9,924
CDD18	0	0	0
Floor Footprint Area (m^2)	118.45	118.45	118.45
Number of Stories	2	2	2
Aspect Ratio	1.5	1.5	1.5
Window-to-wall Ratio	60%	40%	20%
Orientation (degrees) - 90° is south facing	90	90	90
Number of Basements	1	1	1
Wall Height (m)	2.74	2.74	2.74

Overall Wall U-value (W/m^2.K) [R-value]	0.32 [R18]	0.159 [R36]	0.103 [R55]
Attic U-value (W/m^2.K) [R-value]	0.189 [R30]	0.095 [R60]	0.072 [R79]
Foundation Wall Overall U-value (W/m^2.K) [R-value]	0.322 [R18]	0.169 [R34]	0.172 [R33]
Area Weighted Average Window U-value (W/m^2.K)	3.166 [R1.8]	1.704 [R3.3]	0.836 [R6.8]
Area Weighted Average Window SHGC	0.493	0.267	0.25
Air Tightness (ACH at atm)	0.75	0.35	0.1

Table 10. Operational and electrical specifications of a single dwelling house.

Occupants	
Number of occupants	4
Occupancy Schedule	NECB 2017 Schedule G Table A-8.4.3.2.(1)-G
Setpoints	
Heating	20°C
Cooling	25°C
Setbacks	None
Lighting	
Target Illuminance	150 lux
Normalized Power Density	6.25 W/m^2
Lighting Schedule	Simplified: 12am to 4pm - 0 4pm to 11pm - 1 11pm to 12am - 0
Equipment	
Power Density	4.25 W/m^2
Equipment Schedule	NBC 2015 Table 9.36.5.4
Domestic Hot Water	
Peak Flow Rate	0.0000167 m^3/s
Usage Schedule	NBC 2015 Table 9.36.5.8

Daily usage	225 L / house
Natural Ventilation	
Ventilation Rate	0.24 ACH
Schedule	Simplified: 12am to 4pm: 0 4pm to 6pm: 0.5 6pm to 10pm: 1 10pm to 11pm: 0.6667 11pm to 12am: 0

Table 11. BECOP values for a house located in Abbotsford, BC (Climate Zone 4).

	Building Envelope Thermal Efficiency		
	Low	Typical	High
Total Energy [kWh]	70,658	39,494	22,779
Energy Per Total Building Area [kWh/m^2]	199	116	70
Heating Energy [kWh]	51,650	21,934	5,816
Cooling Energy [kWh]	1,019	128	7,780
BECOP-Heating Energy	0.1%	0.2%	0.7%

Table 12. BECOP values for a house located in Iqaluit, NU (Climate Zone 8).

	Building Envelope Thermal Efficiency		
	Low	Typical	High
Total Energy [kWh]	165,024	80,958	34,586
Energy Per Total Building Area [kWh/m^2]	464	238	106
Heating Energy [kWh]	146,738	63,426	17,604
Cooling Energy [kWh]	144	9	0
BECOP-Heating Energy	4.0%	9.2%	33.2%

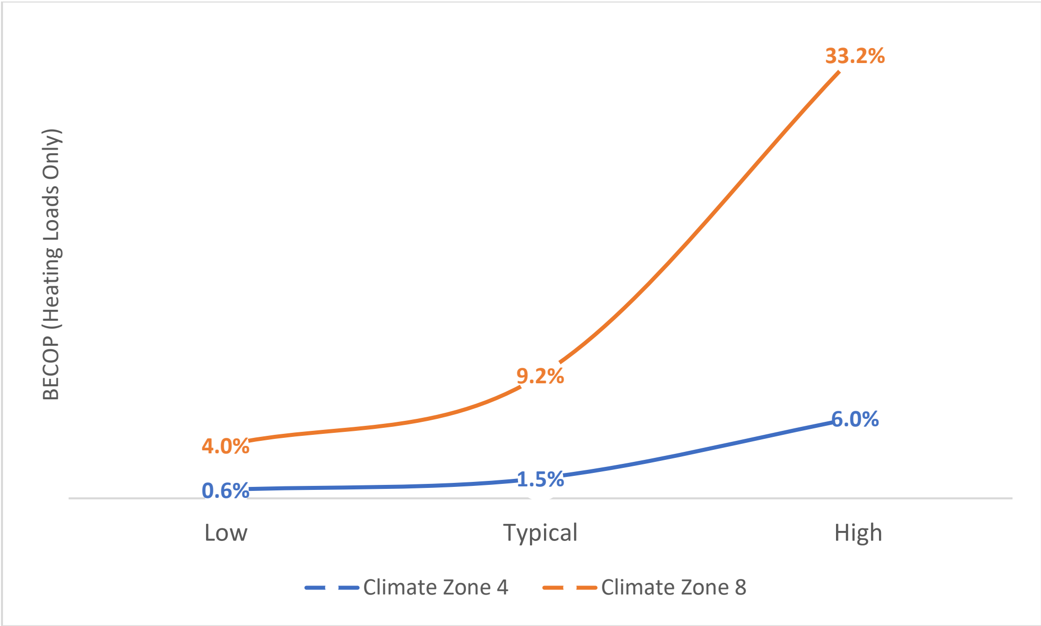

Figure 5. BECOP values versus level of construction.

For further context, the target heating energy consumption of 15 kWh/m^2.year is the current limit prescribed by Passive House [34]. Accordingly, the house annual heating energy consumption would be 4,872 kWh for all climate zones. The corresponding BECOP values for Climate Zones 4 and 8 are 0.8% and 120%, respectively. The results clearly show the deficiency and inconsistency in the approach currently followed by codes and standards pertaining to building envelope. The target needs to be a measure of efficiency or performance relative to a datum if energy efficiency is in fact the intended measure.

3.2 Sensitivity of BECOP

The results given in Tables 11 and 12 are further studied to determine the sensitivity of the metric to the Climate Zone, design specification level, and both. For Zone 4, one observes that the BECOP values go from 0.1% to 0.7% and for Zone 8 from 4.0% to 33.2%. A ratio of approximately 9 is observed between the low and high construction regardless of the Climate Zone. By examining the BECOP values across the Climate Zones, one observes a ratio of approximately 60 between Zone 8 and Zone 4 regardless of the design specification level. The fact that the same building envelope has a higher BECOP in Zone 8 relative to Zone 4 may be counterintuitive if the traditional logic that the envelope in Zone 8 would lose more energy than in Zone 4 simply due to the temperature difference. Instead, BECOP yields the improvement/opportunity potential by quantifying the relative performance of the design to the ideal design while accounting for all the building properties including internal heat gains. The values indicate that BECOP is sensitive to the climate and that the measure is uniform when the properties of the building envelope are the same. When both the climate and the properties change, the ratio of BECOP is no longer the same as the impact is amplified by the changes in both the climate and building envelope properties. The ratio of BECOP of a highly efficient building envelope in Zone 8 to a poorly efficient building envelope in Zone 4 is about 475 whereas the ratio of BECOP of a highly efficient building envelope in Zone 4 to a highly efficient building envelope in Zone 8 is about 6. This response is reflected in Figure 5 where the increase in BECOP as a result of an improved building envelope performance is significantly higher in Climate Zone 8, where the improvement is more impactful. On the other hand, in Climate Zone 4, where the improved envelope has a more modest and linear impact, the BECOP displays that effect. These results clearly show the sensitivity of BECOP to the coupled effect of building envelope performance parameters in combination with the Climate Zone, along with the building's properties and characteristics.

4. Application of BECOP

Three case studies are presented to demonstrate the applicability of the proposed metric. The case studies were selected to demonstrate the strength of the metric and the associated benefits/potentials, as well as identify potential weaknesses.

4.1 Case Study 1 – Design of a New House

The first case study illustrates how a design professional could employ the BECOP to take inventory of the design decisions. For reference, the house is to be constructed in Toronto, ON with a total living space specified by the owner to be approximately 240m^2 without the basement and a ceiling height of 2.74m. A 20% window to wall ratio (WWR) is selected contingent on the energy consumption. City of Toronto, ON is in Zone 5 with a corresponding HDD18 and CDD18 of 3892 and 292, respectively [35]. Accordingly, the variables to evaluate are the building orientation and the building envelope specifications. Firstly, the effect of WWR is investigated by considering three possibilities that are fairly high: 20, 40 and 60%. The properties and characteristics of the house's pre-design are given in Table 13. The corresponding energy consumption and BECOP are given in Table 14. Given the relative thermal properties of the building envelope, the energy consumption due to heating is expected to increase as WWR goes from 20% to 40%. This impact of doubling WWR is captured by BECOP as it drops from 5.4% to 4.4% reflecting a 19% relative loss in efficiency which can be misleading as the actual loss in efficiency is only 1%. By further increasing the WWR to 60%, BECOP decreases to 3.7% representing a 30% and 1.7% drop in relative and absolute loss of efficiency, respectively. These results show the significant difference between absolute and relative measure. The actual loss in efficiency is 1% and 1.7% as the WWR increases from 20% to 40% and from 20% to 60%, respectively. Therefore, reporting a relative loss in efficiency of 19% and 30%, which has been the norm for building envelope, can mislead the designer and lead to an erroneous design.

The heating energy consumption increases 23% and 47% as WWR goes from 20% to 40% and from 20% to 60%, respectively. These results show that a percent increase in energy consumption is linearly proportional to WWR. Comparing the heating energy consumptions with those of BECOP one observes that the former yields a linear trend whereas the latter a non-linear one. Moreover, the information in the form of percent change in energy consumption can be misleading as the results imply that the energy efficiency of the building decreased by 23% when WWR is increased by 20%. A non-apparent and critical implication is the sensitivity of the relative change in energy consumption to the building envelope properties, i.e. as the building envelope properties change the increase in heating energy consumption will be significantly different for the same WWR increases. In contrast, the change in the BECOP reflects the impact of WWR as it is a measure of the overall building envelope efficiency relative to a fixed ideal system.

In brief, BECOP provides an efficiency pattern that can be used to optimize the design. The loss in BECOP is indicative and intuitive for a designer to understand a loss in efficiency as opposed to increased energy consumption.

Table 13. Effect of window-to-wall ratio.

	Window-to-Wall Ratio (%)		
	20	40	60
Floor Footprint Area (m^2)	118.45	118.45	118.45
Number of Stories	2	2	2
Aspect Ratio	1.5	1.5	1.5
Orientation (degrees) - 90° is south facing	90	90	90
Number of Basements	1	1	1
Overall Wall U-value ($W/m^2.K$) [R-value]	0.159 [R36]	0.159 [R36]	0.159 [R36]
Attic U-value ($W/m^2.K$) [R-value]	0.086 [R66]	0.086 [R66]	0.086 [R66]
Foundation Wall Overall U-value ($W/m^2.K$) [R-value]	0.322 [R18]	0.322 [R18]	0.322 [R18]
Area Weighted Average Window U-value ($W/m^2.K$)	1.704 [R3.3]	1.704 [R3.3]	1.704 [R3.3]
Area Weighted Average Window SHGC	0.267	0.267	0.267
Air Tightness (ACH at atm)	0.25	0.25	0.25

Table 14. Effect of window-to-wall ratio on BECOP.

	Window-to-Wall-Ratio (%)		
	20	40	60
Total Energy [kWh]	37,756	42,619	47,735
Energy Per Total Building Area [kWh/m^2]	109	123	138
Heating Energy [kWh]	20,197	24,899	29,752
Cooling Energy [kWh]	29	172	400
BECOP-Heating Energy	5.38%	4.36%	3.65%

Secondly, the orientation of the building using a 40% WWR is investigated by varying the East-West orientation (0° to North) to the North-South orientation (90° to North). The results in the form of energy consumption and BECOP are summarized in Table 15. They reveal that a change in orientation has no effect on the BECOP value as it goes from 4.38% to 4.36%. Although the change in BECOP value is considered negligible, nonetheless it shows the sensitivity of the metric to small changes in energy consumption. The heating energy consumptions give the same results. In brief, the minor change in BECOP and heating energy implies that the orientation has no impact on the house energy consumption for this particular configuration.

Further examination of the results provides an important insight into how the BECOP can provide additional information. With the slight drop in the heating energy from 24,917 kWh to 24,899 kWh, it implies a small benefit can be realized with the house oriented in the N-S direction. In contrast, the BECOP value drops from 4.38% to 4.36% indicating a decrease in the efficiency. This implies that the ideal building experienced a more significant drop in heating energy than did the investigated house, indicating that there are more potentials to improve the building envelope in the orientation facing N-S than in the E-W direction. This information, which is not intuitive from the heating energy consumption alone, is valuable and can lead the designer down the path of seeking further improvements.

Table 15. Effect of building orientation on BECOP.

	Orientation	
	0° to North (Facing E-W)	90° to North (Facing N-S)
Total Energy [kWh]	42,717	42,619
Energy Per Total Building Area [kWh/m^2]	124	123
Heating Energy [kWh]	24,918	24,899
Cooling Energy [kWh]	234	172
BECOP-Heating Energy	4.38%	4.36%

4.2 Case Study 2 – Retrofit Design for an Existing House

Upgrading the thermal resistance of an existing 2-storey single family detached dwelling with a basement located in Toronto, ON is sought. The house is rectangular in shape with an aspect ratio of 1.5, floor area of 118.5 m^2, wall height of 2.74 m, 40% WWR, and long side facing South. The energy renovation measures (ERMs) include thermal upgrading of windows, walls, walls and windows, roof, or walls, windows and roof. Assuming some budgetary constraint, the designer could estimate what improvements for each option could be achieved within the constraints. If BECOP is calculated for each of the options, the designer would have sufficient information to select the most impactful and cost-effective option. Tables 16 and 17 show the effect of several energy retrofit measures (ERMs) improving the overall wall U-value from 0.159 $W/m^2.K$ (R36) to 0.142 $W/m^2.K$ (R40), improve window U-value from 1.704 $W/m^2.K$ (R3.3) to 0.921 $W/m^2.K$ (R6), both improvements, improving the overall U-value of the attic from 0.086 $W/m^2.K$ (R66) to 0.071 $W/m^2.K$ (R80), and all three improvements combined.

Table 16. ERM designs.

	ERMs					
	Base	1 (Walls)	2 (Windows)	3 (1 & 2)	4 (Attic)	5 (1, 2 & 4)
Overall Wall U-value ($W/m^2.K$) [R-value]	0.159 [R36]	0.142 [R40]	0.159 [R36]	0.142 [R40]	0.159 [R36]	0.142 [R40]
Attic U-value ($W/m^2.K$) [R-value]	0.086 [R66]	0.086 [R66]	0.086 [R66]	0.086 [R66]	0.071 [R80]	0.071 [R80]
Foundation Wall Overall U-value ($W/m^2.K$) [R-value]	0.322 [R18]	0.322 [R18]	0.322 [R18]	0.322 [R18]	0.322 [R18]	0.322 [R18]
Area Weighted Average Window U-value ($W/m^2.K$)	1.704 [R3.3]	1.704 [R3.3]	0.921 [R6]	0.921 [R6]	1.704 [R3.3]	0.921 [R6]
Area Weighted Average Window SHGC	0.267	0.267	0.240	0.240	0.267	0.240
Air Tightness (ACH at atm)	0.25	0.25	0.25	0.25	0.25	0.25

Table 17. Effect of ERMs on BECOP values.

	ERMs					
	Base	1	2	3	4	5
Total Energy [kWh]	42,619	42,316	35,199	34,897	42,477	34,756
Energy/Total Building Area [kWh/m^2]	123	123	102	102	123	101
Heating Energy [kWh]	24,899	24,650	17,497	17,250	24,758	17,111
Cooling Energy [kWh]	172	171	168	167	171	165
BECOP-Heating Energy	4.36%	4.41%	6.21%	6.29%	4.39%	6.35%

From Table 17, it is evident that improving the windows provides the most savings in terms of energy consumption, and improving the wall and attic U-values provides minimal benefit. Considering that the wall and attic insulation levels of the base-house are quite high relative to current codes and construction practices, this indicates that they have reached the point of diminishing returns with today's technology. This knowledge is useful to the designer to make an informed decision. Moreover, the BECOP provides insight that is not evident from the energy consumption data, i.e., increasing the wall and attic thermal resistance using today's technology would not improve the efficiency of the building envelope without improving other aspects of the building such as orientation, geometry, air tightness, WWR, etc. This insight allows the designer to investigate other options such as the ones presented in Case Study 1 as well as air tightness improvement, window shading, etc. As such, the path and design decisions will be guided by the information embedded in the relative changes of the BECOP. The absolute value of the BECOP also provides insight into the fact that there is still an opportunity to improve the performance with novel and advanced materials and systems, that may guide the designer to further explore. Moreover, the BECOP value accounts for the whole building envelope and rewards for having a compatible thermal resistance envelope, something which cannot be discerned directly from energy consumption data.

The changes in the BECOP value for each ERM relative to the base case are compared to the corresponding changes in energy consumptions, Table 18. The BECOP values indicate that Option 3 provides a 1.93% increase in the building envelope efficiency, which is significantly less than the 31% reduction in the heating energy consumption. Moreover, changes in BECOP values of 0.05% and 0.03% are obtained for upgrading the wall and attic with a corresponding 1% and 0.6% reduction in heating energy. BECOP provides a measure of the building envelope efficiency which is different from energy savings. Although it is more appealing to report a saving of 31% in heating energy consumption, albeit it is a real measure, it dissuades from realizing that the heating energy saving potential for the house is significantly greater than the one obtained.

Table 18. Percent reduction in energy consumption due to ERMs.

	ERM - 1	ERM - 2	ERM - 3	ERM - 4	ERM - 5
Total Energy	0.7	17.4	18.1	0.3	18.5
Energy / Total Building Area	0.1	17.4	17.6	0.3	18.0
Heating Energy	1.0	29.7	30.7	0.6	31.3
Cooling Energy	0.9	2.5	3.4	0.7	4.1
BECOP-Heating Energy	0.05	1.85	1.93	0.03	1.99

4.3 Case Study 3 – Regulatory Compliance

Efficiency and COP are measures used to assess the absolute performance of equipment or systems. For buildings, these absolute measures are only prescribed for the electrical and mechanical equipment and systems such as the lighting, HVAC, pumps, fans, etc. For the building envelope thermal performance, there are no absolute measures for efficiency or COP. Present practice is to either specify a minimum thermal resistance for each sub-system (wall, window, roof, and floor) based on the climate zone, or an annual energy use and/or intensity. The regulators supporting rationale stems from comparative energy consumption, statistical analysis, or both. Case study 2 is a prime example where a 31% reduction in the heating energy consumption would resonate well with regulators not knowing that the savings correspond to 1.93% increase in the building envelope efficiency. In brief, the current approach does not provide an absolute measure of the thermal efficiency of the building envelope or account for the thermal compatibility of the various sub-systems that form the building envelope system.

BECOP is a simple, practical and performance-based metric for regulating the energy efficiency of building envelopes. For illustration purpose, a BECOP of 4.50% as a minimum requirement for the City of Toronto is prescribed. This approach specifies an absolute efficiency measure as well as allows flexibility in the design to achieve the desired BECOP. From the results of the previous case studies, one can establish that a 20% WWR would meet the requirement, Table 14. From Table 15, the thermal resistance of the base house needs to be upgraded enough to improve its BECOP from 4.4% to 4.5%. Alternatively, upgrading the windows would provide more than sufficient improvement to comply with the regulation. Different approaches, designs or combinations are possible to achieve the same BECOP target, which is directly related to actual energy performance. Moreover, BECOP can be used early in the design process to account for the orientation and geometry, among other properties at no cost.

Replacing a target heating energy consumption with a BECOP value would revolutionize the regulatory compliance requirements. It would transform a deficient and inconsistent approach currently followed by codes and standards pertaining to building envelope to a measure of its performance relative to a well-defined datum. Moreover, BECOP measures the efficiency of the building envelope while accounting for the entire building properties, characteristics, climate-zone, occupancy and operation.

6. Discussion

BECOP was developed to measure the thermal performance of the building envelope in a useful, consistent and systematic manner. The benefits and strengths of BECOP were noted while analysing the results of the case studies. A noted weakness is the range of the BECOP given the low efficiency of the building envelope compared to the ideal system. Nonetheless, this weakness can become a catalyst for designing a more efficient building envelope. Furthermore, BECOP values showcase the energy saving potentials that can be realized with newer and innovative building envelope systems.

The ideal system was inspired by a perfect opaque vacuum (zero conductivity, convection and radiation properties), which was then translated into practical values for BECOP. BECOP can accommodate future advances in the building envelope technologies as it is a measure of performance and not a direct measure of efficiency.

For this study, BECOP was measured while accounting for all internal gains. An alternative approach is to exclude the internal gains. Accordingly, BECOP will provide an impartial measure of the building envelope thermal efficiency for both heating and cooling.

As demonstrated through the case studies, a significant capability of the metric is its ability to capture the performance and compatibility of the system as a whole, which traditional metrics currently used (total energy, TEUI, TEDI, etc.) are not able to capture since there is no datum built-in. The BECOP achieves this target by ensuring that a compatible design is rewarded relative to an incompatible design. This results in a manual optimization of certain parameters, which is not possible to achieve without having an optimal design (or "idealized" design). Another advantage of the BECOP is its ability to penalize missed opportunities in the system design, and reward the captured opportunities. For example, the BECOP will capture and inform the designer if for a particular orientation, improving the thermal resistance of particular components does not offer a benefit. On the other hand, the same properties for a different orientation would further penalize the savings not achieved by that configuration. This is further demonstrated when comparing a fixed and absolute space heating EUI target, (e.g. 15 kWh/m^2.year). This target does not address the increased difficulty in achieving a set level of performance in colder climates, with the argument that colder climate requires a thermally efficient building envelope among other energy systems. The corresponding BECOP values identify which building envelope still has room for improvement (BECOP 0.8% in Climate Zone 4), and which one requires to be 20% more efficient than the idealized system (BECOP 120% or 1.2 in Climate Zone 8). These BECOP values clearly show the impracticality of imposing a space heating EUI target for all climate zones.

7. Conclusions & Recommendations

The results from this study have revealed the following conclusions:

- Current practices and regulations pertaining to the building envelope are arbitrary and do not provide any measure of efficiency.

- Results of scientific studies reveal that higher requirements than the minimum requirements prescribed by codes and standards yield a more economical and ecological sound design and a necessary step to achieve NZEB.
- An idealized material/system equivalent to a near-perfect thermal insulator is proposed to assess the thermal resistance of the building envelope.
- BECOP, which provides a performance measure, captures any deviations from an idealized system.
- BECOP yields a measure of efficiency and thermal compatibility of the building envelope.
- BECOP is invariant to the calculation methods and applicable to all building types and climate zones.
- BECOP values expose the difference between energy savings and building envelope efficiency.
- BECOP provides insights to identify missed opportunities for a particular location, weather conditions, and geometry.
- QCA for the purpose of energy efficiency design is misleading in establishing the optimal design and deterrent to technology development as the potential energy savings are never realized.
- Maximum BECOP value of 35% reveal the inefficiencies in the current building envelope technologies and the building envelope energy saving potentials.
- Although BECOP is demonstrated for heating energy, its application to cooling energy depends on the internal energy.
- BECOP is applicable in design, regulation and optimization of the building envelope.
- BECOP provides a measure of the distance away from an optimized/idealized design.
- The BECOP, or similar metric that utilizes a fixed ideal datum is a step in the right direction to revolutionize the regulatory methodology and philosophy, and subsequently demand innovation from the construction industry, ensure a positive economic and ecological impact.

This study is a first step in highlighting the differences between heating energy savings and efficiency of the building envelope. Accordingly, it is recommended that further studies be carried out to refine the properties of the ideal datum as well as carry extensive sensitivity analyses to guide in the interpretation of the BECOP values.

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Chapter 6 – Energy efficiency decision-making model using data analytics

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Partial Least Squares Projection to Latent Structures (PLS), Energy model classification, Energy design models, Code compliance models, Energy codes and regulations

Abstract

Energy consumption of buildings is required to be estimated for the design of new structures, for the rehabilitation or retrofit of existing structures, for demonstrating compliance with regulations, rules, and specifications, as well as for developing these rules, regulations, and the like. Currently popular tools appear to be too complex to be practical tools for most of the intended purposes above, where these tools appear to solely focus on most accurately estimating energy consumption and compromising on practicality of use. Stochastic models developed based on more detailed building performance simulation (BPS) models and focused on the practicality and suitability for the intended uses provide a promising option. As a framework for developing stochastic models, a partial least square projection to latent structures (PLS) model was developed using a relatively small dataset of 396 observations, 13 inputs, and 3 outputs. The outputs were annual energy consumption and insulation cost analogue. The inclusion of costs in the model allow for a qualitative assessment of cost versus the reduction in the estimated energy consumption. The resulting model had a root mean square error of estimation (RMSEE) of 12.9% of the mean and was sufficiently practical to be programmed into a spreadsheet as to provide instantaneous and simultaneous calculation of annual energy consumption and cost analogue. This allowed for use in design of new and retrofit projects (via linear programming/optimization or analysis of various energy consumption measures), design and application (enforcement) of regulation, labelling programs and incentive programs. This demonstrates that the framework for stochastic models are appropriate to allow energy consumption to be treated in a scientific yet practical methods.

1. Introduction and Background on Energy Models

It is well established, through almost all the papers referenced in this study, as well as many other papers on this topic, that it is beneficial to substantially reduce energy consumption of the built environment. The benefit of energy reduction can be argued to exist regardless of the energy source. In general terms, to reduce energy consumption of the built environment, energy simulation tools or energy models are required [1]–[4].

Energy modelling and energy modelling tools have various purposes and goals [5], and they are used by different professionals [6] in similar or varying manners. Energy models can be used for design of new structures [7], investigating retrofit strategies [8], [9], benchmarking building performance [10], urban energy modelling for multiple buildings [11]–[13], sensitivity studies [14], etc.

With the various uses of energy models, the energy models all appear to have a single goal, which is to better and more accurately estimate energy consumption, even with the recognition that these estimations include significant assumptions and errors such as occupant behavioural factors and averaged weather data.

In general, an energy model for a building is a calculation which, from various inputs, estimates overall energy consumption of that building [6], usually broken down for different end uses (e.g. HVAC, plug loads, etc.). To include all the various calculations required for energy estimation, such as space heating and cooling (which in itself is a complex calculation of multiple sources of thermal losses and gains), domestic hot water usage, lighting, equipment and plug loads, ventilation and leakage loads, etc., energy models have become complex and require a large number of inputs [1], [15]–[19]. This complexity has given rise to different types of models as discussed in the next section.

In this study, a PLS algorithm is used to create a decision-making tool that simultaneously assesses costs and energy consumption in a practical way to allow for decisions made early in the design stage be made based on actual measures. This study serves as the proving ground to demonstrate how difficult and abstract concepts can be scientifically evaluated. The next sections provide the reader with sufficient background to fully appreciate the need for such tools, and understand what other options are currently available in this vast field of study.

1.1 Classification of Energy Models

There is not a single or unique categorization to classify energy models [1]. However, most of the literature seems to make a clear distinction between energy models based on first principals and energy models based on statistical methods, techniques and models, with others adding a third category which combines both approaches [1], [3], [16], [20].

Energy models based on first-principals, throughout the literature, are sometimes referred to as engineering methods, fundamental methods, first-principal models, white-box models, high-resolution models, forward or classical approaches, energy simulation programs, physical models, and detailed models. In this paper they will be referred to as detailed building performance simulation (BPS) models or tools. These types of models are further divided in various ways, including but not limited to computational fluid dynamics (CFD) approach (e.g. Comsol), Zonal Approach, and Multi-zonal approach (e.g. EnergyPlus, TRANSYS, ESP-r) [3], or simplified levels such as degree-day (DD) methods (DD, Modified-DD, and Variable-DD) (e.g. HOT2000), and detailed such as sequential and simultaneous methods (e.g. EnergyPlus, TRANSYS, and ESP-r) [21].

Energy models based on statistical methods were developed in response to the complexity of the BPS models, and they have attempted to match the accuracy of these models. These models, sometimes called black-box models, are typically categorized based on their underlying algorithms. The most popular being regression models [15], [20], [22]–[25], artificial neural networks (ANN's) [4], [11], [16], [17], [24], [26], [27], and Support Vector Machines (SVM) [17], [23], [24], [27]. Other data analytic and machine learning algorithms are also used [4], [12], [13], [27]. These statistical models have been proven to have adequate performance in terms of accuracy of estimation [16], [17], particularly when the training dataset is large and has a sufficient number of inputs.

Hybrid models, sometimes referred to as grey-box models, appear to utilize elements from both. They are also designed to achieve the same estimation accuracy as the BPS models, but with less inputs. Some examples of hybrid models are shown in literature [28]. The hybrid systems vary much more significantly in nature are not clearly defined. Some statistical models are considered hybrid models because they were calibrated and/or generated using energy models, and other BPS models are considered hybrid because some derivations or relationships solving for a particular aspect (e.g. thermal losses through soils) are based on empirical formulations.

Other classifications are present in the literature with most being a rearrangement of the BPS models, statistical models and hybrid models [1]. All of these models can be steady-state or dynamic models, which adds another dimension to the classification. All classification systems discussed here are based on the inner workings of the models themselves. However, in another dimension, one could classify these models based on their appropriate use. This is further discussed in the next section. Figures 1 and 2 below show a matrix and graphical representation or visualization of the classification of energy models. Note that hybrid models have been omitted for clarity, and can be added in the same fashion.

	BPS Methods (White-box)				**Statistical Methods (Black-box)**			
	Degree Day Methods	Bin Methods	Sequential Methods	Simultaneous Methods	ANN-based	SVM-based	Regression-based	Others
Steady-State Models								
Dynamic Models								

When classifying a model by trying to insert it in one of the cells in the matrix above, consider using the intended use as the label within each cell. The uses could be code compliance, accurate estimation of a single structure, accurate estimation of urban areas, retrofit design, design tools, policy evaluation, etc.

Figure 1. Matrix classification of energy modelling software.

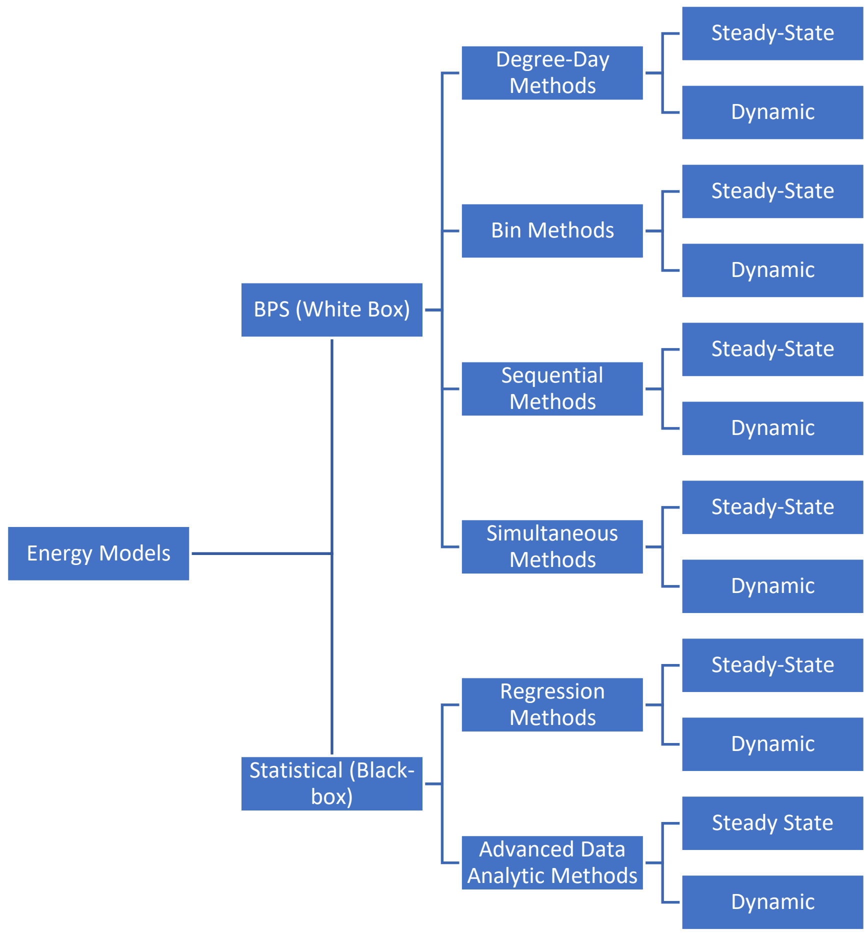

Figure 2. Hierarchical chart of classification of energy modelling software.

1.2 Model Uses

Classifying models based on intended use could be the best approach especially in context of policy makers, code developers, regulators, and the general public. It has been the experience of the authors that for those groups of users, the perception is the all energy models are created equal, with the underlying philosophies and algorithms being of no practical significance. However, the complexity of models is usually simplified to improve practicality, and the level of simplification is highly dependent on the intended use of these models. Some of the common uses of models include:

- Accurate estimations (as accurate as possible with current tools and knowledge),
- Code compliance

- Decision making, and
- Many others.

See Figure 3 for a graphical representation.

Models intending to accurately estimate energy consumption of a specific building or group of buildings form the majority of models. The most accurate algorithm is typically desired, limited only by high-level computing practicality issues (e.g. computational time and capacity). Once these are programmed, they are then wrapped with scripts or user interfaces that attempt to make the tool more practical. It should be noted that these tools require a large number of inputs, and if all inputs are entered exactly as they were to occur in a reality, including occupant behaviour, leakage rates, weather data, time-varied and load-varied equipment efficiencies, etc. then in theory, the estimated or calculated outputs should match the reality. At the current time, testing this hypothesis is not practical, nor particularly useful, however it is stated here as a hypothetical desired goal for the development of these types of models.

Code compliance models are tools that are developed mainly to determine whether or not a particular design is code compliant. In some instances, BPS models whose goal is to accurately estimate energy consumption are also used for code compliance and is an acceptable use. However, the inverse which is to use code compliance tools as BPS models requires the user to proceed with extreme caution. Code compliance tools are calibrated and include hidden assumptions and rulesets to achieve two objectives:

1. The results allow the modeler to determine whether or not the proposed modelled structure meets minimum code requirements, and
2. Is sufficiently practical for energy modelers to use in order to ensure or encourage code adoption, adherence, and compliance.

The outputs of the code compliance models are sometimes in kWh/time (usually year) or kWh/(m^2 × time) which has caused some users to assume these numbers are accurate estimates of energy consumption. In most cases the models themselves are built as such with simplified algorithms (such as bin methods) and then subsequently build in assumptions consistent with code and policy requirements to provide calibrated results as opposed to strictly accurate estimations.

Code compliance models typically require the modeler to enter around 100 inputs (depending on the actual tool), which describe a full building, and then run the model. The modeler can then vary the inputs and rerun the model to obtain results, and compare the results. Although this is current practice, a tool specific for decision making would provide much more added benefits, and this is the goal of the model framework developed in this work.

Design decision making models or tools, particularly early design decision making models, form the minority of available tools, and not widely discussed or available, if they exist at all. In some instances, they have been reduced to rules of thumbs derived from degree-day methods or other historical methods. Some statistical models are better at this task, however, in most cases, they are not designed specifically for this use. Design decision making models must provide:

1. Scientifically-based outputs available with few inputs at early design stages,
2. Provide insight into the building design, and
3. Sufficiently practical where different decision points can be tested in a matter of seconds, by non-energy modelers.

There are additional intended uses that may make use of energy modelling, such as policy tools (although they could be grouped as decision making tools), urban energy consumption which also could address interactions between multiple buildings, optimization, etc., with optimization being of particular importance. Due to the complexity of energy models, even the simplified of them, optimization itself becomes quite complex and almost exclusively an academic exercise which dedicated research addresses this topic [18]. It is worthy to note that in literature and other work in the field, optimization should be described more specifically whether it is model optimization, optimization of retrofit design decisions, or optimization of design, not to mention the need to describe the variables being maximized or minimized, and the constraints. In the design tool described here, the optimization presented is to minimize energy consumption and insulation costs (or cost analogue) under various constraints.

Intended Use	Building		Urban	
	Steady-State Models	Dynamic Models	Steady-State Models	Dynamic Models
Estimating Energy Consumption				
Code-Compliance				
Design				
Other				

When classifying a model by trying to insert it in one of the cells in the matrix above, consider using the algorithm as the label within each cell. For example, ANN, SVM, bin, CFD, BPM, etc.

Figure 3. Classification of energy models based on intended-use.

1.3 Data Analytics

From the above discussion, it has been established that energy simulations/modelling/calculations are complex, but so are other scientific phenomena such as the structural behaviour of concrete and wood, chemical processes, etc. At the times when these phenomena were required to be used in practical situations, even after the knowledge was available, the computing power was not available to address these complex behaviours. As a result, designers and practitioners, reverted to experience, or in more technical terms empirical evidence, and later on statistical models. The capacities of wood and concrete structures, and even the variability of capacities in steel, are even to this day, calculated and estimated based on statistical and empirical data. Since today's computing power was not around when most of these models were developed, they did not solely focus on the accuracy of the estimation, but on the practical need and adequacy, and calibrated it to the acceptable level of risk. This allowed the maturity of the structural field, where today's computation power and advanced and complex models are now utilized to improve models, to create and validate new materials, etc., without the need for these complex models in the typical design processes.

The reason this subject is brought up here, is that it is possible to suggest that the proliferation of numerical tools and computational power coincidentally at the same point in history that energy calculations have become of high importance due to its relationship with energy conservation, potentially derailed the practical side and focused on accuracy over usability. With this advancement of the knowledge on energy modelling more-or-less aligning with the advancement of computing powers, the focus has seemingly been solely on improving this ability, and in most cases, practicality has been sacrificed. Although it can be claimed that increased accuracy of building energy models is required [6], it is the author's opinion that increased practicality and development of early-stage decision making tools are equally, or potentially to a larger extent, also required.

Learning from lessons from other fields, statistical or stochastic models provide a valid alternative to the development of practical design tools. This is further validated as earlier discussed, by the fact that statistical techniques were used to develop models that target accurate estimations of energy consumptions. Adding to that discussion the advancement of the statistical tools with data analytic techniques and algorithms, the opportunity appears to be great to benefit from this advancement. The advances in computing power can be leveraged now to generate datasets required to develop stochastic models, as well as to analyse this data using advanced techniques such as artificial neural networks, support vector machines, regression models, decision trees, projection to latent structures (or partial least squares - PLS), etc. Each of these methods and algorithms is described fully in literature. In this paper, PLS models were developed and used, and as such only this algorithm is presented.

1.4 Early Design Decision Making Tool Framework

As discussed, statistical models have been developed for various applications. They are stochastic tools employing various methods These methods, depending on their specific setup and training dataset fall into the areas of data analytics, big data, machine learning, deep learning, artificial intelligence, etc. The main commonality between all methods is the need for large datasets, which are not readily available [29]. As a result, the use of such models remains limited to specific applications due to the limitation of the available datasets. These methods are mentioned here since the work within this paper utilizes the power of such techniques as well, through the PLS algorithms.

The goals and objectives of this paper are to:

1. Overcome the challenges discussed,
2. Propose a framework for developing early stage design decision tools for energy efficient designs, and
3. Demonstrate how these methods can be applied to practically and scientifically evaluate certain design decisions, policies, etc.

Subsequently this framework will be applied to a relatively simplified example or case study on housing and to develop a practical early stage design decisions tools and investigate how it could be used in the design process via trial and error, or preferably, via optimization.

To achieve those goals, this paper begins with a description of the overall methodology or philosophy of the study followed by a description of the methods and techniques used in conjunction with that overarching methodology. A brief theoretical background will be provided along with the basis for calculations. The subsequent tool is described and its usage is described along with its limitations. Three examples are then provided on how the tool could be used in a hypothetical design (one as an optimization exercise and the other as a design exercise) and retrofit design context. Finally, the resulting model is evaluated by identifying its strengths and weaknesses, along with recommendations for future work to better utilize the strengths, and improve on the weaknesses of the resulting tool.

2. Methodology

With the current practice, early stage design decisions are made based on experience, univariate knowledge, qualitative intuition, and cost considerations. This is a result of the only available option is to calculate the energy consumption using available models, where these models are relatively complex and require many inputs (i.e. decisions) and advanced tools to solve mathematically. These models used are mostly based on first principle calculations (mainly BPS models), or simplified code-compliance models, and require specialist modelling tools/software to process the large number of inputs. This complexity makes most available tools impractical for early stage design decision making.

Statistical models may provide a potential solution if developed for that specific intended use. Current statistical models do not fit that description as they target accurate predictions, and as a result, the complexity of these statistical models disguises the interactions of the inputs, and results in a black-box approach.

For this study, the main focus is on a practical model for use early in the design decision making process. The models should have improved practicality and provide an improved understanding of the system, resulting in decision making insights that consider some of the major compatibility and interaction issues that exist within the complex heat/energy transfer systems of a building. The use of partial least square (or projection to latent structures – PLS) methods [30] with careful considerations of inputs and outputs can overcome many of the problems faced by other stochastic models.

For developing the desired model, the following are some simplified and general steps applied:

- Data collection and creation of a dataset. This requires defining the source of the data, the inputs, and the outputs.
- Development or training of the PLS model, including testing, evaluation, and validation.
- Demonstrate the use of the model. Due to the focus on the practicality of the resulting model, a test on the possible practical uses is an important step to consider.

2.1 Experimental Design

For statistical models, a large number of observations is desired and preferred. That is around the order of magnitude of tens of thousands of observations. This is not particularly challenging when the dataset requires only energy consumption data since simple scripts or open-source tools compatible with EnergyPlus [31] and ESP-r [32] are readily available to run an automated full parametric study. However, when other outputs are also required to be calculated, especially when developing a limited model to test the hypothesis, a large dataset becomes impractical and the number of observations needs to be minimized. With a small dataset, to ensure that the desired scope is covered, techniques such as fractional factorial designs should be utilized [33], [34]. For slightly larger datasets, other techniques may be used such as Monte Carlo simulations [15].

This particular dataset was built for other studies using fractional factorial designs. Each model was also then varied for location (i.e. varying HDD65 and CDD65). Other models were also collected and gathered from studies looking at specific aspects of the building envelop. As a result, the dataset included 396 datapoints in the training set, and 36 energy consumption datapoints in the testing dataset, a number which is not justified via factorial designs. For a fully saturated factorial design for 16 inputs, only 32 carefully selected datapoints would be required. Having said that, since the variation in the factors (i.e. inputs) was not strictly controlled for the goals of this study, then the efficiency of the 396 datapoints is reduced.

2.2 Data

The dataset for this study includes inputs (16), outputs (3), and observations (396+36). The inputs include HDD65 (4458 to 10416 days), CDD65 (67 to 4458 days), footprint area (74.82 to 438.26 m^2), number of storeys (1 to 3 storeys), basements (slab-on-grade or single basement), ceiling height (2.44 to 3.05 m), percentage of perimeter facing south (9.9 to 40.1%), south façade area (13.1 to 242.5 m^2), wall U-value (0.106 to 0.531 $W/m^2.K$), attic U-value (0.185 to 0.458 $W/m^2.K$), foundation or slab-on-grade skirt U-value (0.169 to 4.284 $W/m^2.K$), window U-value (0.801 to 5.548 $W/m^2.K$), window SHGC (0.119 to 0.882), area of windows on south façade (0.52 to 83.34 m^2), total area of windows (5.83 to 278.70 m^2), and air infiltration (0.075 to 0.52 ACH at atmospheric pressure). Notable exclusions include HVAC equipment, lighting, plug loads, etc. which were removed either because the ease of replacement at future stages or the fact that they are not usually early-stage design decisions.

HDD65 and CDD65 are numbers calculated from daily temperatures at a particular location. Therefore, they can be considered to describe the location’s weather, i.e. the general area where the building or house is located. These numbers are not the best available descriptors of the weather, and not complete. Weather files for BPS models include hundreds of values to describe the weather, as opposed to just two. However, they were chosen to be used as the indicators for location mainly for their practicality where they are readily and easily available numbers for any designer. Another reason why they were chosen is that they vary for each location, even if they have similar or close weather conditions, as opposed to thermal zones, whose values are not as descriptive, i.e. zone 2 is not twice as warm (or cool) as zone 1. For the desired level of practicality, HDD are CDD were chosen as the best indicators for this study. Note that it was possible to develop a model for each location, which would likely be more accurate, however in seeking practicality, this approach was chosen.

Footprint area is one descriptor of the building geometry, and is a significant factor in energy consumption. It is one the designers always know and consider. It is also one of the most difficult to change after-the-fact.

Number of storeys is another simple and significant descriptor of the building geometry as it relates to energy. It is also one of the most difficult decisions to change after-the-fact. Furthermore, one decision the designer and owner commonly face is how to balance footprint area and number of storeys. The difficulty with using this factor as opposed to area per storey for example is that it cannot accommodate fractions of storeys. Accommodating such variation requires a larger dataset.

Basements is also a geometry descriptor that has significant impact on energy consumption. In this model it was used as basement or slab-on-grade (SOG) design. This is also a decision that is not practical to change after the fact.

Ceiling height or storey height, while describing the geometry, along with footprint are and number of storeys is what determines the volume of the building which is an important factor in energy consumption.

Percentage of perimeter facing south is the first descriptor used to capture the building orientation. This provides insight into the total perimeter of the house and shape as well. This is also a practical number for a designer to calculate and change as they decide the shape of the building or house.

South façade area, which is similar to the percentage of perimeter facing south, however it combines the interaction between the orientation and the ceiling height (volume) of the house. This also is a practical number for the designer to calculate and change during the design stage, and much more difficult to change after the fact.

Wall U-values is the first descriptor of the building envelope. The value should preferably include the thermal bridging impact, cladding, etc. This is a decision to be made early in the design stage and difficult or unfeasible to change afterwards. The inclusion of the thermal bridging, sheathing, cladding, etc. is useful for designers to consider, however if these are similar between the investigated options, then the simple cavity insulation value would work as well. Although this U-value does not include values like thermal mass, if an effective U-value is used, where the thermal mass is accounted for (as a simplification) as a constant U-value, it may be included.

Attic U-values describe the horizontal building envelope or roof. The attic U-value implies that the model includes, and therefore covers, a specific type of roofing system, typical in North America's single-family home design. To expand the scope of the model, additional datapoints with other types of horizontal envelopes, such as cathedral ceilings or flat roofs would need to be added.

Foundation U-values describe the amount of insulation used to insulation basement or foundation walls. If the house has a SOG, this refers to the insulation around the slab perimeter.

Window U-values and SHGC describe the overall level of insulation and the radiation properties of the windows. From an energy perspective, these factors are sufficient to describe the properties of transparent sections of the building envelope.

Area of windows on the south façade and the total area of windows are simple geometric descriptors of the windows layout. This intends to capture the impact of the distribution of the windows around the façade, particularly the South façade for the northern hemisphere, and the quantity (area) of the transparent building envelope.

Air infiltration, finally, can be considered a descriptor for the building envelope as a whole, the air barrier in particular, or simply a measure of quality of construction. For this particular model, as was proved by the data, has the largest impact on energy consumption of a house over the practical range.

The range of variation of each of input values is an important consideration in designing a dataset. The range has to be small enough to capture any smaller variations, and large enough to capture the impact of the change or variation in the data. In this particular case, practicality of each of the factors has to be considered, as there are practical limits placed on most of the factors. Minimum codes or available products usually provide the lower constraint, where the maximum practical values, including short-term technological advances, provide the upper constraint.

The outputs are the annual energy consumption (kWhr/year), energy use intensity (kWhr/m^2.year) and insulation material area × RSI unit value (m^2.W/m^2.K) used as a proxy for insulation material costs. This is an important dimension to include in the model to allow it to predict energy consumption as well as insulation costs, in order to allow design decisions to include costs factors as well as mathematical optimization. Total costs would be recommended to be added to the model to allow a more wholistic cost analysis as well. This is made possible by the fact that PLS accommodates vector outputs (multiple outputs).

Every observation in the dataset represents a house in a specific city with specific features described by the inputs. The energy consumption of each of those houses was estimated using EnergyPlus. The same house was modelled in two or three different cities as well. The energy model provided the annual energy consumption estimation and, when divided by total area would provide the energy use intensity. These two outputs formed two of the three vectors in the output matrix. The reason for using simulated data as well as the modelling assumptions and limitations are discussed in [35].

For this study in particular, it was desirable to include another output that is usually as important a consideration as energy consumption, cost. Some measure of cost would ideally be included to aid in the early-stage design decision. For the development of the framework, it was decided to include a cost analogue for insulation as that cost metric, however total costs would be more desirable to include. Cost of insulation is a function of material costs, installation costs, and location. This variability was quite impractical to include accurately, and as a result an insulation cost analogue was selected independent of these variables. The cost analogue used was insulation material area × RSI unit value (m^2.W/m^2.K). This assumes that material costs and installation costs are directly proportional the volume of material used and the thermal resistance. A few calculations in North America showed this to be a reasonable assumption. This cost analogue formed the third and final vector in the output matrix.

2.3 Energy Consumption Data – Energy Modelling

Within the dataset for this study, each datapoint, i.e. each house, has three outputs: total annual energy consumption, energy use intensity (EUI), and insulation cost analogue. Both total annual energy consumption and EUI can be "measured" or calculated from one energy model for each datapoint / house. The modelling was done using EnergyPlus [31].

In general terms, it is typically recommended not to use modelled or simulated data to create a new model. This recommendation is based on the fact that even a perfect model would be only as good as the model used to generate the data. The practical reality is that no model is perfect, and therefore developing a new model to accurately estimate energy consumption will not provide any improvement its accuracy, and will in fact not be as accurate as the model used to develop the data. The general recommendation is to use actual or measured data, which means using real houses for the dataset. The general recommendation was not followed in this case, and simulated data were used for several reasons:

- → The aim of this study is not to create another tool that accurately estimates energy consumption. As discussed, it aims at developing a metric that does not require complex modelling. As a result, a model that approximates the results of a BPS modelling tool such as EnergyPlus is the desired result.
- → Measured data from existing houses does not exist in a usable format [29], and creating such data is not possible without making major assumptions or conducting destructive exploration to measure all the inputs (e.g. wall construction and cavity insulation).
- → Measured energy consumption is a function of whether conditions, which is unlikely to match the weather data assumed in whether files. Similar discussion applies for occupant behaviour and plug loads usually represented by idealized schedules in modelling. Although one could make the necessary adjustments for whether data, it is much more challenging to do for occupant behaviour, without continuous monitoring of occupants, which is not practical for large datasets.
- → For simulated data, the variation in the data can be controlled using design of experiment techniques (e.g. fractional factorials) to cover a specific scope of applicability, which for happenstance data collected on real houses, that is usually a challenge.
- → For statistical models for the estimation of energy consumption, modelled or simulated data is typically used.
- → Finally, one major advantage is that in anticipation of new technologies or worst-case scenario analyses, datapoints or houses with higher or lower than usual performance than

the existing building stock can be simulated, while the variation for measured data is limited by the variation within the existing building stock.

The houses were modelled using some of the following common elements or assumptions:

- All houses modelled using similar HVAC equipment. It is known that what is considered typical equipment for HVAC varies across various locations. The HVAC system used (e.g. electrical baseboard heaters versus forced air natural gas furnaces) were not included as variables in the model and held constant across all datapoints. This is mainly to isolate for building envelope factors as much as possible. Having said that, the dataset could be expanded to include such variations by adding additional factors.
- All houses used natural gas water heaters. The size of the water heater varied with the area of the house. The schedule of operation was compliant with the NECB 2017 [36] or NBC 2015 [37]. The consistency across datapoints in effect removes the impact of such factors, or in other words, blocking of controlled disturbances. As with HVAC equipment, this is mainly to isolate for building envelope factors as much as possible. Having said that, the dataset could be expanded to include such variations by adding additional factors.
- Plug loads, both intensity and schedules, as well as all other schedules, were assumed to be as described in the NECB 2017 or NBC 2015. This means that the developed metric is more closely aligned with these codes.
- General constructions and assemblies followed typical North American construction for the most part. For some intentional variation, non-typical residential construction was used, such as precast concrete, and the construction was approximated based on what would be a possible construction or assembly. In all cases, a simplified estimation of thermal bridging impacts was included in the calculations, and the U-values in the factors used are for the overall assembly, which includes thermal bridging.
- The houses were assumed to be a single zone for HVAC purposes, even when there is a basement. The basement and upper floors are controlled via the conditions on the ground floor.

2.4 Partial Least Squares Projection to Latent Structures (PLS)

PLS is a method within the family of methods sometimes referred to as latent variable methods. These methods work on the notion that input and output data are correlated in most practical situations and may not be clear. In simple terms, the data matrices are broken down into several matrices using eigen value decomposition. When the decomposition is only done on the input matrix, it is usually referred to as Principal Component Analysis (PCA). This technique is sometimes used to ensure the input data in uncorrelated prior to use in other algorithms that cannot handle correlated data such as multiple linear regressions and artificial neural networks. With this decomposition, the mathematics provides quantifiable measures of the hidden correlations and provide some useful insights into correlation structures.

Geometrically, the eigen values satisfy two conditions by definition. The first is that the eigen vector is the direction which explains the most variance. This is the only condition for the first eigen vector. The second condition is that all eigen vectors also are orthogonal to all other eigen vectors. This orthogonality condition is what ensures independence of the data and an important concept. For most matrices these directions do not necessarily have a physical interpretation, however for tensors describing physical systems (usually 2-D or 3-D), physical interpretations can be made and are often the basis of the design and analysis of these systems.

In PLS, this concept is extrapolated further, where the decomposition is optimized in order to allow for regression between the input and output vectors. In geometric terms, this means that the direction or weight vectors (similar to the eigen vector in PCA) are optimized to best explain the variance in both the input and output matrices. In PLS models, the data is broken down into scores (T for the input matrix and U for the output matrix) and weights (in PCA terminology referred to as loadings) (w for the input matrix and c for the output matrix), the number of which are dependent on the number of components used (A). The number of components is analogous to the polynomial order in linear regression or the number of hidden layers in artificial neural networks. So as in these other methods, adding components arbitrarily may lead to overfitting. In PLS, this challenge is resolved and addressed using cross validation methods [38]. For a detailed mathematical discussion on the basics of PLS see the work of Svante Wold’s and John MacGregor’s teams [30], [39]–[41].

It is worth noting that other methods popular in the field such as SVM, decision trees, and artificial neural networks were used in many other studies though for different purposes. The main reasons the PLS algorithm was found to be best algorithm for this work are:

- → The PLS model and underlying algorithm is designed to handle correlated data, where most other regression model have to assume non-correlated, i.e. independent data. This is a particular challenge since energy data are generally correlated. The main impact of having correlated data in a PLS models is that coefficients may be distributed over the correlated data, not giving the real measure of each. However, when all these coefficients are included, this becomes a non-issue.
- → The PLS model is well-suited for small datasets as is the case for this study.
- → Within the PLS model, while using the model in any new capacity, outliers or out-of-scope data can be easily calculated by calculating the standard prediction error (SPE) and Hotelling's T^2 and their confidence intervals. SPE determines if a new datapoint is outside the bounds of the model (near the edges). Hotelling's T^2 determines if the combination of factors that describes the new datapoint is out-of-scope for the model, which occurs if similar combination was not included in the dataset used to create the model.
- → The PLS model can handle multiple outputs as we did in this case. This, along with the linear nature of the PLS model, is key when multiple objectives may be desired for optimization, e.g. energy consumption versus cost of construction.
- → Additional benefit for future implementation of machine learning algorithms and the ability to handle missing data from imperfect new datapoints were also a consideration in the choice of a PLS model.
- → Most importantly for this study, a PLS model and algorithm provides valuable insights into the correlations between inputs, outputs, and inputs and outputs. This insight is what was used to develop the metric.

For this study, a PLS model was developed using seven cross validation groups. The model coefficients for both energy consumption and the insulation cost analogue are used to develop a model which estimates the impact of the various design decisions on energy consumption. This model is presented in the remainder of this paper.

3. The Model

The model was first developed using all input factors and outputs. The model was then further refined by analysing two-factor interactions and some second-order terms particularly by looking at the variable coefficients or variables important to projection (VIP) plots [42]–[44]. The RMSEE and R^2 were the main metrics that were focused on in determining if the model is improved. The final model had an RMSEE of 12.9% of the mean and R^2 0.906 for energy consumption and 14.6% and 0.91 for the cost analogue. For the training set, when outliers in climate Zones 4 and 8 were added, which are clearly outside the scope of the model, the RMSEP was approximately 37% of the mean, removing Zone 8 data, the RMSEP was less than 20% of the mean, and for data within the scope of the model the RMSEP was approximately 15%, comparable to the RMSEE. For such a small dataset, these values are adequate for the purposes of this study. Also, no outliers were removed which would artificially improve these values as well as limit the scope of the model.

The observed versus predicted plots are shown in Figure 4 and 5 for energy consumption and insulation cost analogue respectively. The tails which reflect the low energy consumers and the very high energy consumers appear to be outliers, but after investigation of these points they were determined to be appropriate where they appear to be outliers simply as a result of lack of datapoints in that same region. A larger dataset would likely rectify this issue as well. For the cost analogue prediction, there also appears to be lack of adequate predictability near the tails, which is also as a result of the range of data. This is further reflected in the SPE versus Hotelling's T^2 plot shown in Figure 9. Furthermore, the figures presented a possibility of structured errors which may be a reflection of a non-linearity that is not captured by the model. To investigate, the Observed versus Residual (Predicted minus Observed) were plotted (not shown here) and no structure to the error or residual was observed.

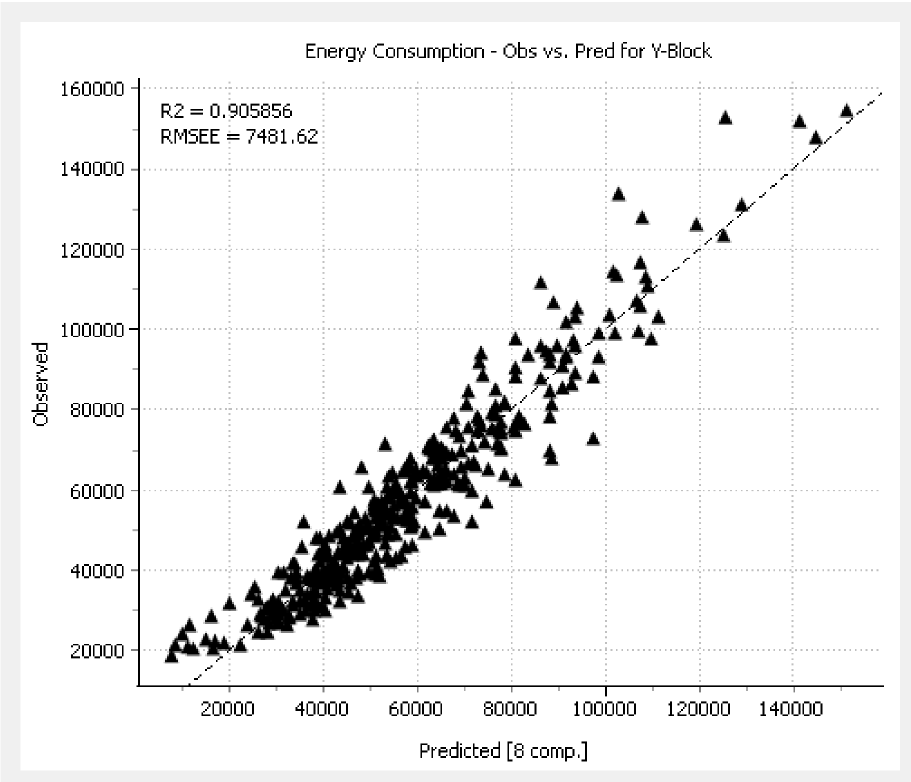

Figure 4. Energy consumption observed vs. predicted for all 8 components.

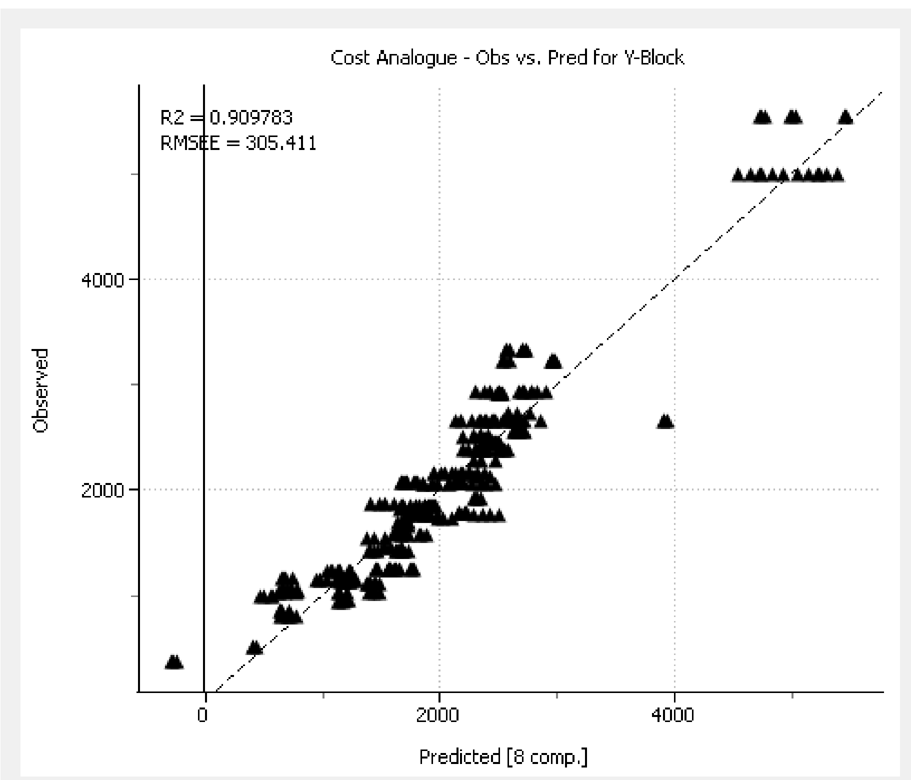

Figure 5. Cost analogue observed vs. predicted for all 8 components.

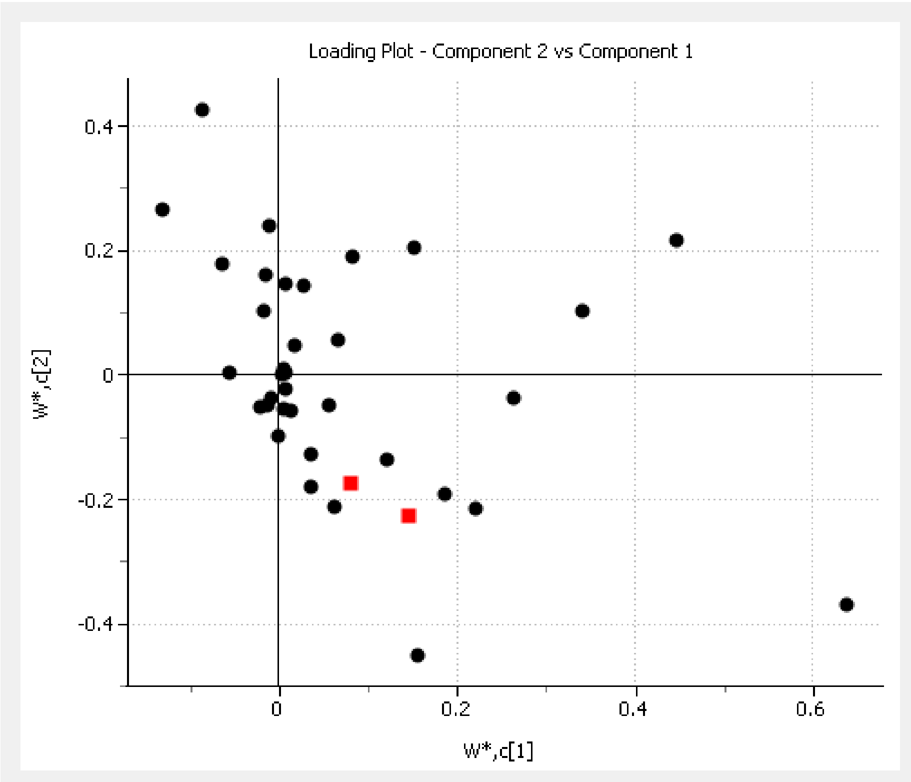

Figure 6a. Loadings plot for components 1 and 2 (explaining 46.3% of the variance).

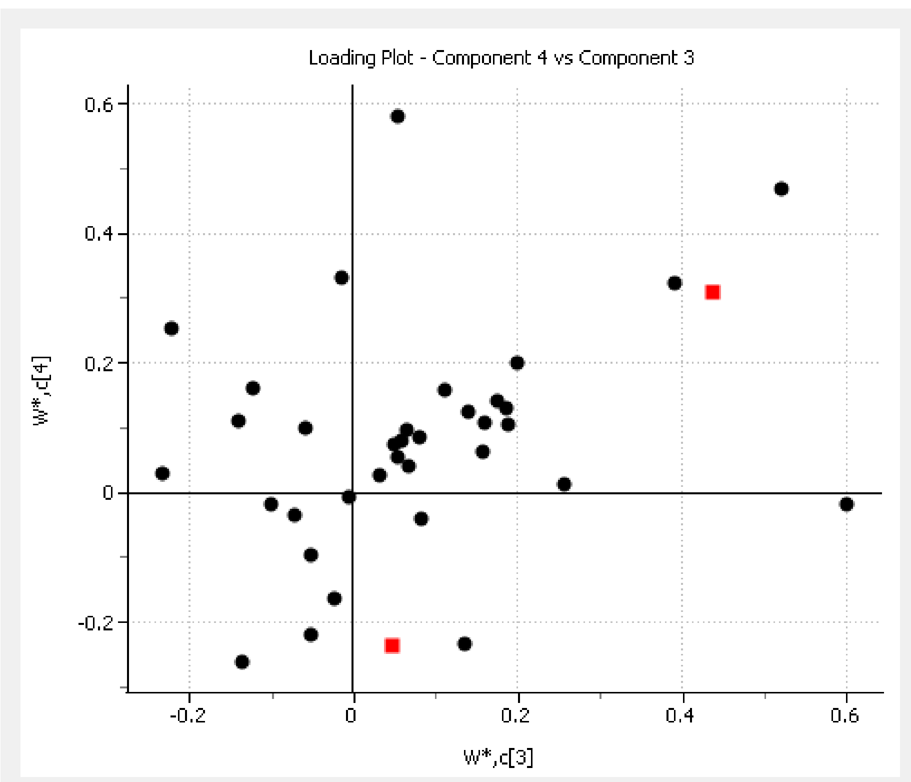

Figure 6b. Loadings plot for components 3 and 4 (explaining 7.8% of the variance).

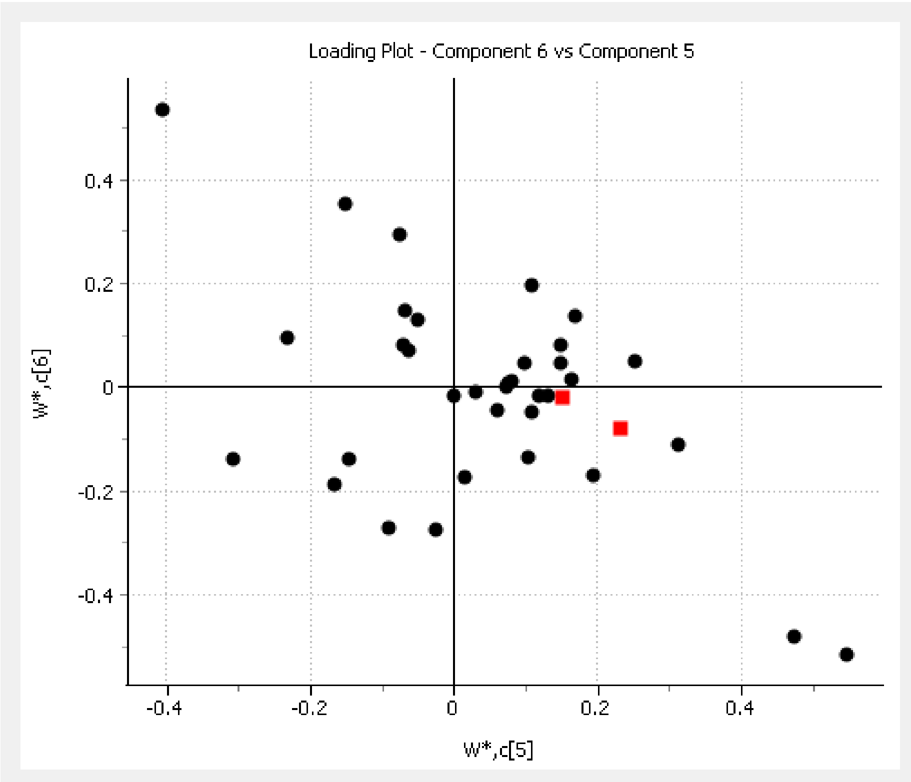

Figure 6c. Loadings plot for components 5 and 6 (explaining 13.6% of the variance).

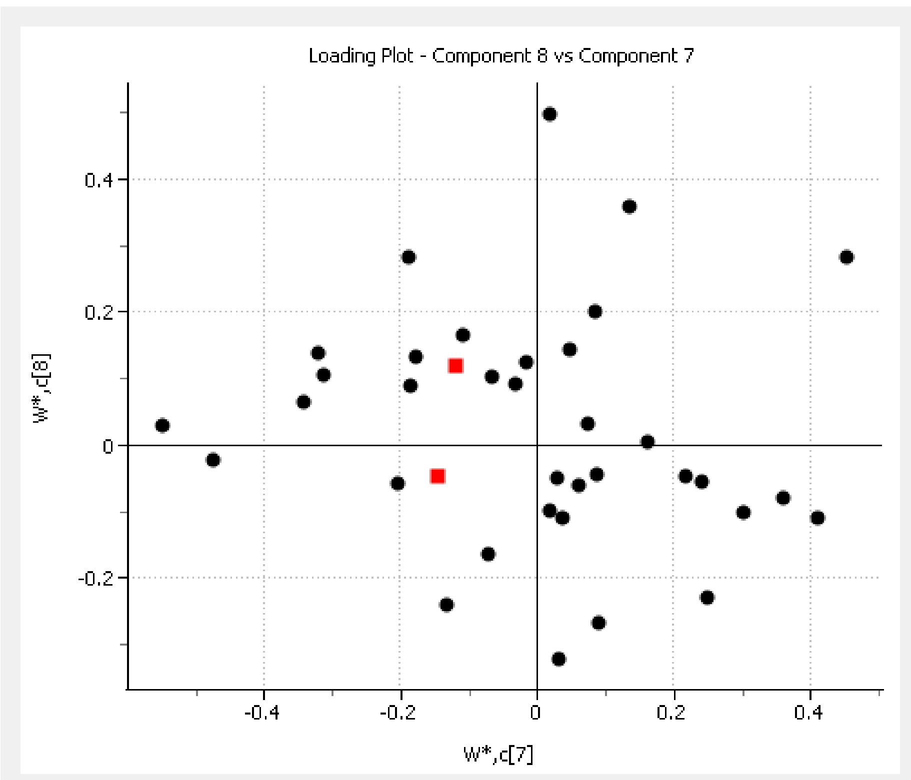

Figure 6d. Loadings plot for components 7 and 8 (explaining 4.7% of the variance).

Note that w (w-star), or r are used instead of w to allow for better interpretation of the PLS models. These are the deflated form of w, i.e. they are from the input matrix* [44], [45].

The score plots (T2 versus T1, T4 versus T3, T6 versus T5, T8 versus T7) are shown in Figures 7a to 7d. These show the scatter of the scores which represent the datapoints independent from one another. Two main observations are worth noting in these Figures. The first is the outliers, as previously discussed appear outside the confidence interval ellipses shown, however upon inspection they are not considered as outliers, and therefore kept within the model. Note that removing them would improve the model metrics (RMSEE and R^2), however the more desired approach would be to add additional datapoints. The second is the clustering that is observed, particularly in T2 versus T1 (Figure 7a) which represents the largest portion of the variance in the data (46.3%). This clustering opens the possibility of using the PLS model as a classification model. This was not pursued here as it was outside the objective of the project and it is thought that additional datapoints would be required for that work to be useful. It is worth noting that the order of components does matter because each component progressively explains more of the variance than the next component. This can be seen in Figure 8 below where the components respectively explain 36.7%, 9.5%, 4.8%, 3.0%, 4.0%, 9.6%, 2.6%, 2.1%.

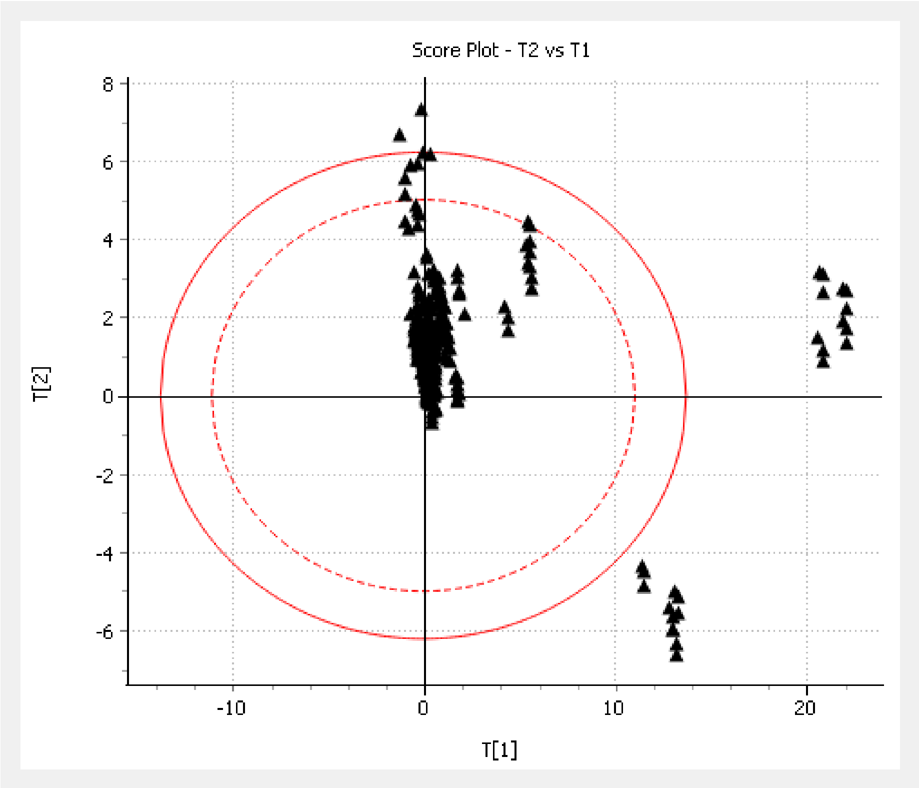

Figure 7a. Score plot for components 1 and 2 (explaining 46.3% of the variance).

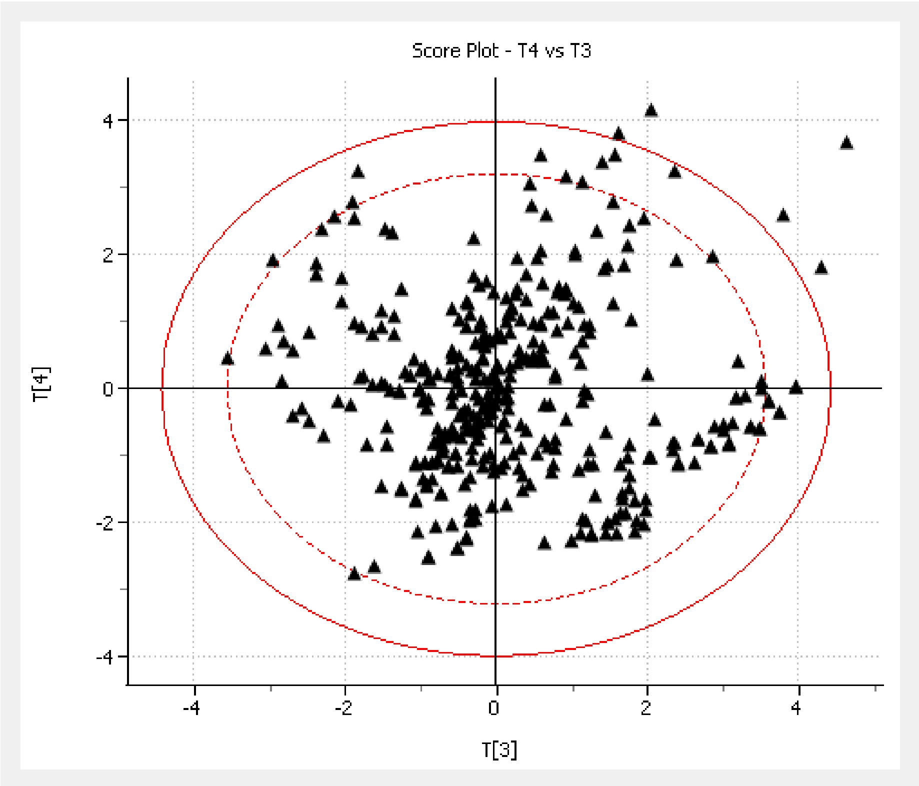

Figure 7b. Score plot for components 3 and 4 (explaining 7.8% of the variance).

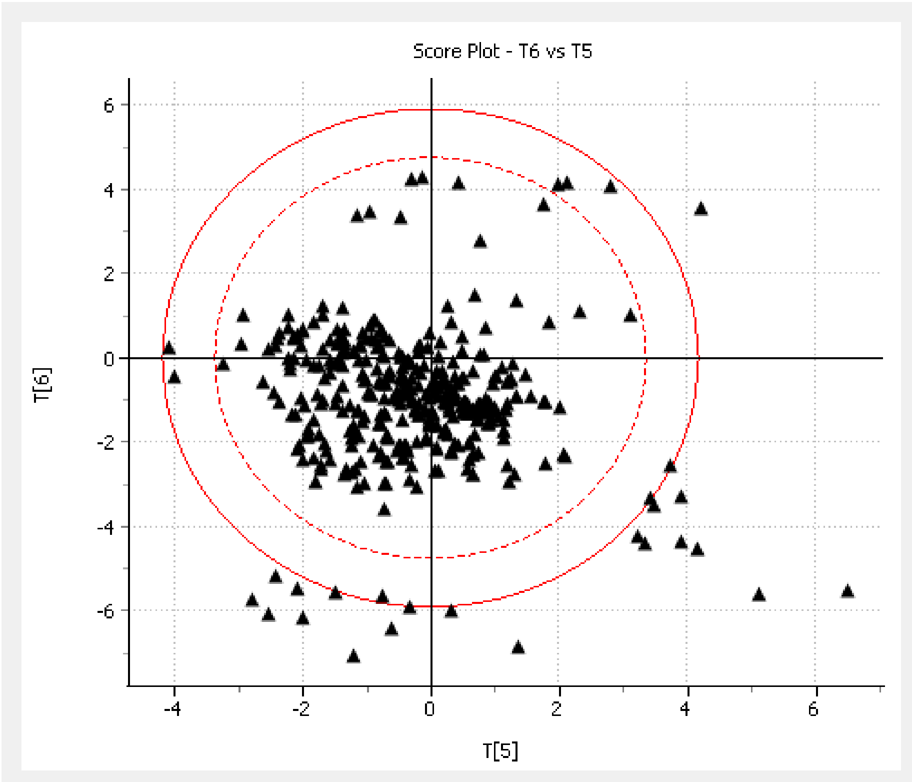

Figure 7c. Score plot for components 5 and 6 (explaining 13.6% of the variance).

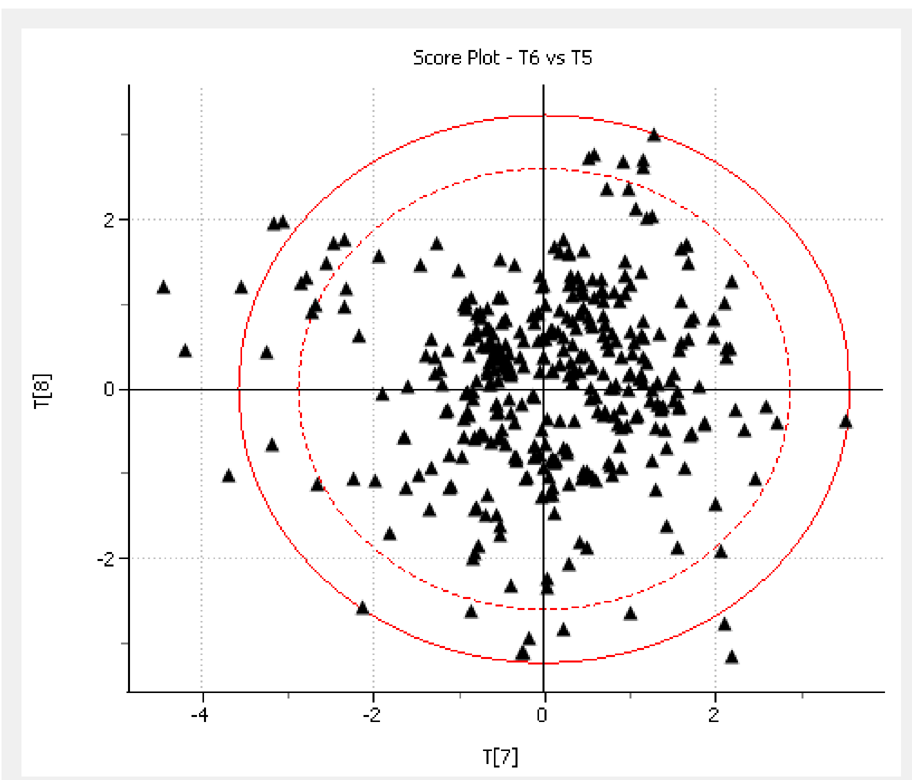

Figure 7d. Score plot for components 7 and 8 (explaining 4.7% of the variance).

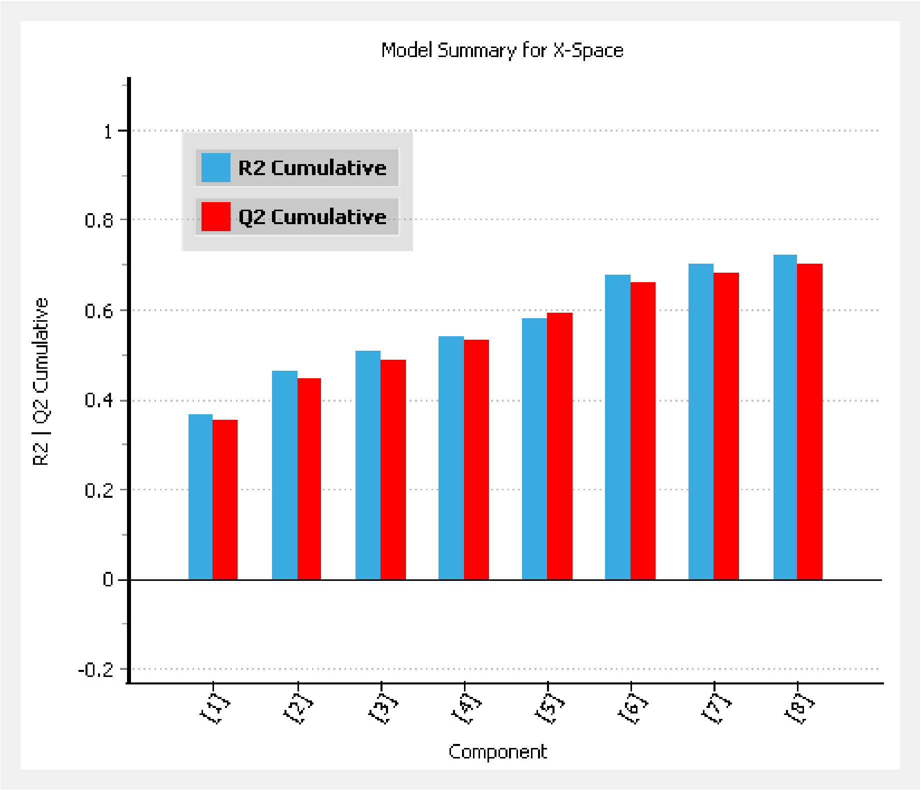

Figure 8. Model summary for each component.

Finally, a very useful plot is the SPE versus Hotelling's T^2 shown in Figure 9 below. SPE refers to standard prediction error. The higher the SPE the more error there is in the prediction. This aligns with the observed versus predicted plot shown in Figures 4 and 5 above. A point with high SPE refers that the model is not adequately predicting the values. On the other hand, Hotelling's T^2 is a measure of the "distance" of a datapoint from the centre of the model, i.e. mathematically identifying the scope of bound of applicability of the model. Datapoints outside the confidence intervals for Hotelling's T^2 imply that they are outside the scope of the model. This plot confirms the previous assessment where datapoints that appeared as outliers, would be expected to have a low Hotelling's T2 and a high SPE. In Figure 9, there are no datapoints in the quadrant for high SPE and low Hotelling's T2, confirming that those datapoints are not outliers, and just need additional supporting datapoint in order to expand the scope of the PLS model.

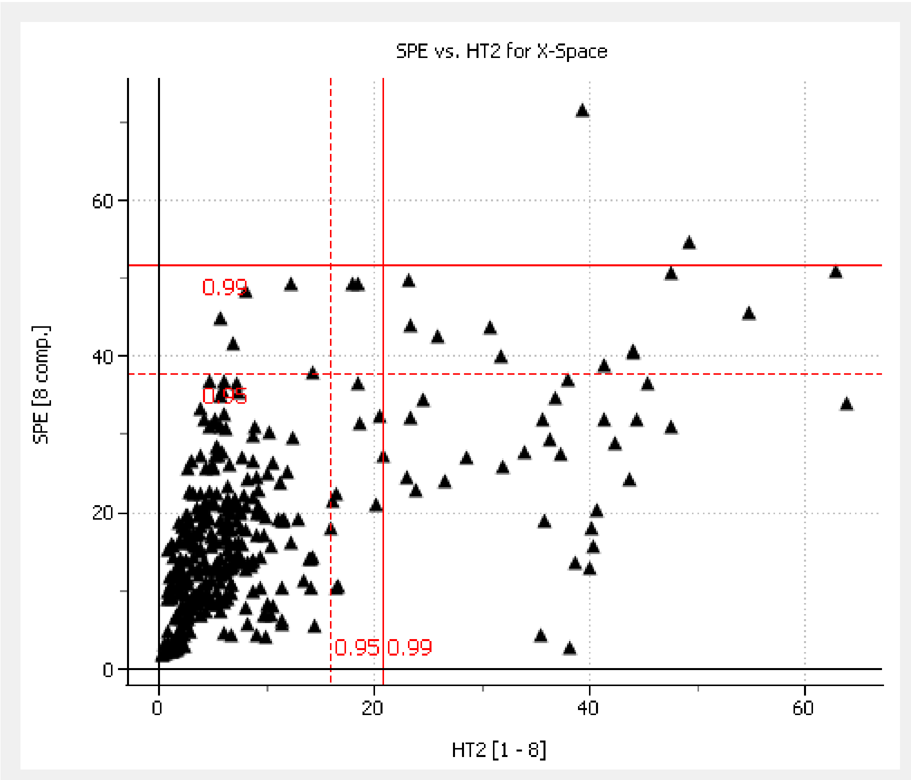

Figure 9. SPE vs. Hotelling's T^2 plot.

The model coefficients (centred and scaled) bar plots are shown in Figures 10a and 10b below for Energy Consumption and Cost Analogue respectively. Figure 11 shows the bar plot of the variables important to projection (VIP) for the input space. The VIP is a measure of what variables are important to the describe the whole input space. The VIP is calculated as a weighted sum of the squares of the PLS model weights for each component [43] as show below:

$$VIP_{Ak} = \sqrt{\sum_{a=1}^{A}\left(W_{ak}^{2}(SSY_{a-1} - SSY_{a})\right)\frac{K}{SSY_{0} - SSY_{A}}}$$

Where K is the number of variables in the input matrix (X-space) (16 in this case), W is the model weights, $SSY_{\#}$ is the sum of squares of Y-Space after # component [44].

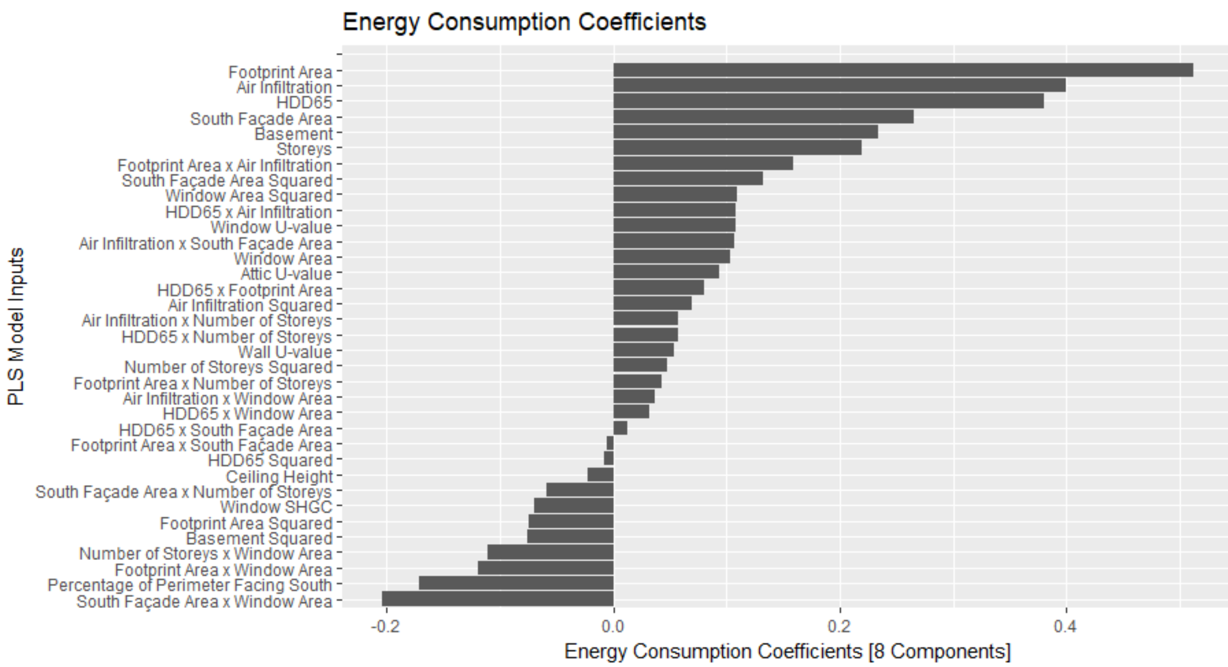

Figure 10a. PLS model coefficients for energy consumption.

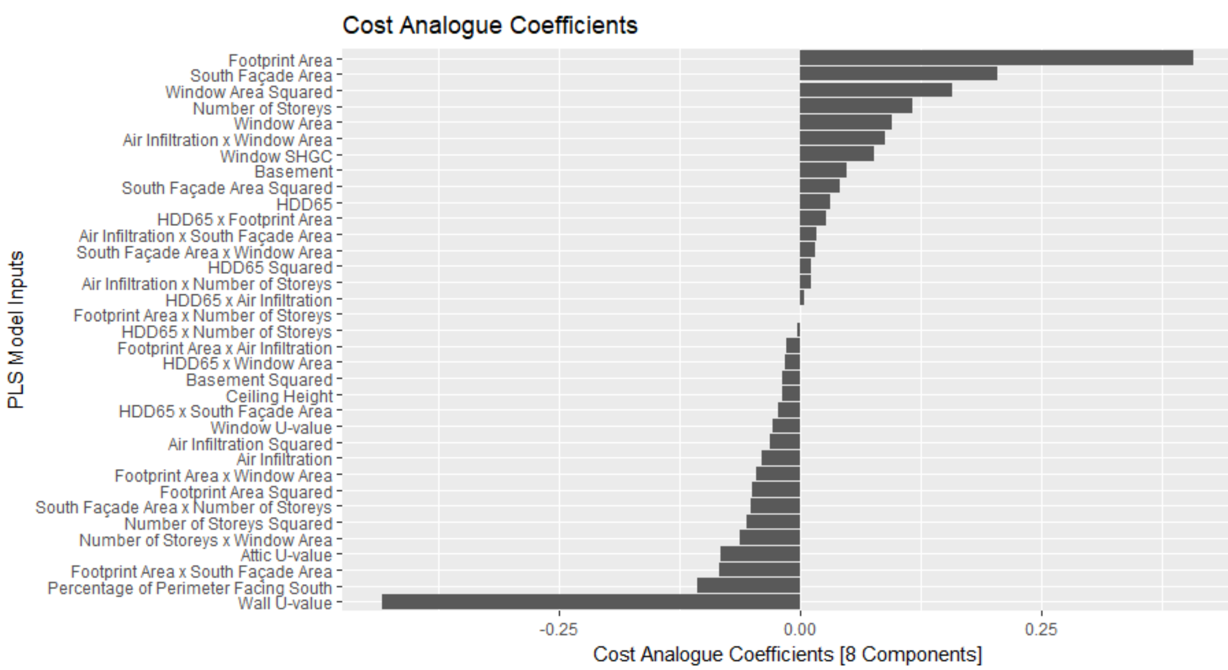

Figure 10b. PLS model coefficients for cost analogue.

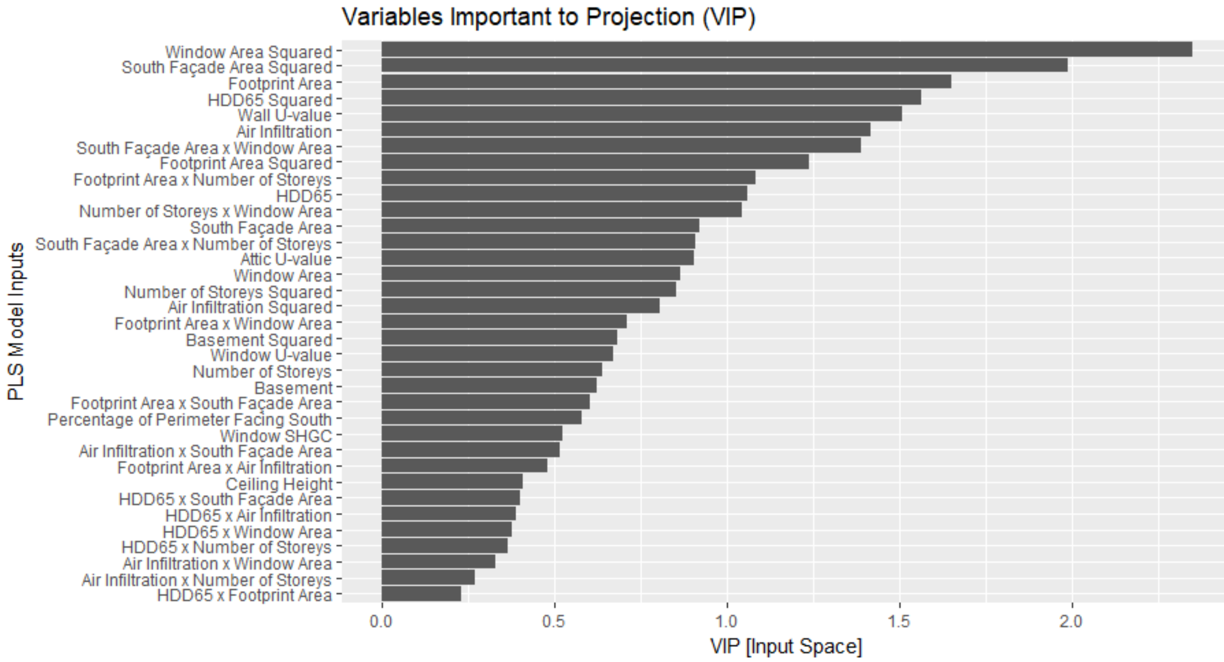

Figure 11. PLS model VIP plot for the input-space.

From the energy consumption coefficients plot (Figure 10a), the top five factors that would influence energy consumption are the footprint area, air infiltration, HDD65, south façade area, and basements. These are as expected, and the coefficients allow to quantify the measure of the influence of each of those factors and others, within the scope and limitations of the dataset and subsequent PLS model. This allows for the development and use of a tool as an early-stage decision-making tool for energy. Then considering the cost analogue, from the coefficients plot (Figure 10b), the top five factors that would influence the cost (or cost analogue) are the footprint area, wall U-value, south façade, window area (squared), and number of stories. The coefficients also help quantify the cost analogue impact within the scope and limitations of the model. These components together can allow for the development of a practical early-stage design tool, that considers both cost (limited to cost analogue of insulation in this example framework) and energy consumption.

Where the coefficients plots identify factors important for energy consumption and cost considerations as determined from the data and subsequent model, the VIP plot shows factors that are important for the PLS model in its calculations and estimations. The top five variables important to the projection refer to higher order terms which are important. It also shows that there are no factors that need to be removed (VIP ~ 0) to free up a degree of freedom to add a higher-order term.

Finally, there were some minor anomalies that were observed due to the limited number of multiple factor interactions. This would be rectified by a larger dataset which would allow the addition of higher order terms and multiple-factor interactions.

3.1 Early-Stage Design Decision Making Model

The main features of this type of model are the number and type of inputs required, the calculation of a cost metric using the same inputs, the model linearity, and instantaneous and practical calculations. The inputs required are typically either decisions that are made at an early stage within the design (e.g. geometry and orientation), or they are constraints known to the designer at the onset of the design (e.g. location). Entering a small number of inputs (13 in this example of the model), would allow for the simultaneous and instantaneous calculation of both an estimate for energy consumption as well as a cost metric. This would provide the decision maker with practical, instantaneous and valuable information. These features allow for a multitude of applications, four examples of which are described briefly here.

The first two potential uses of such a model are for the design of new structures. Section 3.2 describes how the linearity of the model could be leveraged to provide a design starting point via a multi-objective function optimization minimizing both cost and energy consumption. Section 3.3 provides an example where the designer can use the model in a spreadsheet form, as shown in Figure 12 below, to manually investigate the impact of various design options and decisions to be made.

The third potential use of such a model is in the design of a retrofit program in order to determine the best way to invest a fixed budget to reduce energy consumption. Section 3.4 provides an example of such an application.

The fourth potential types of uses are for the design of requirements that apply to a generalized set of structures. This is usually the challenge in designing regulations, the enforcement or application of regulations (by owner, authorities having jurisdiction, auditors, etc.), the design of labelling programs, and/or the design of public or private incentive programs. Such a model could be used in multiple ways to achieve two goals: (1) allow the regulators to focus on the desired outcome(s), typically reduction of energy consumption in this context, and (2) provide the designers with a target, a practical tool, and the freedom to choose the method to achieve those targets.

	Fill Here	Units	
HDD65	7120	days	Location - Obtain from Local Codes or ASHRAE
Footprint Area	200	Sq.m	Geometry - Design/owner decision
Number of Storeys	1		Geometry - Design/owner decision
Percentage of Perimeter Facing South	22.2	%	Orientation - Design/owner decision
Basements	1	0 or 1	Geometry - Design/owner decision
Ceiling Height	3.05	m	Geometry - Design/owner decision
Wall U-value	0.2366	W/Sq.m.K	Building Enevlope - Design decision
Attic U-value	0.26	W/Sq.m.K	Building Enevlope - Design decision
Window U-value	1.2	W/Sq.m.K	Building Enevlope - Design decision
Window SHGC	0.3		Building Enevlope - Design decision
Total Area of Windows	70	Sq.m	Geometry & Building Envelope - Design/owner decision
South Façade Area	70	Sq.m	Orientation - Design/owner decision
Air Infiltration	0.24	ACH at atm.	Building Enevlope - Design specification and decision

RESULT		
Energy Consumption	51828	kWh
Insulation Cost Analogue	1872	Units

Figure 12. Demonstration of how the model could be programmed into a simple spreadsheet.

3.2 Optimization for Energy Consumption and Cost

Since the resulting PLS model is a linear model, i.e. can be described by a linear combination of factors, the optimization of such a problem is much simplified into a linear programming problem. One main advantage of solving a linear programming optimization problem is that it is mathematically guaranteed that the optimum (maximum or minimum) is a global maximum or minimum. This makes the result unique. The second advantage is the tractability of such optimization problems which make them a practical design option.

In the optimization calculations, the objective function is to minimize both the energy consumption and cost analogue equally weighted. An example in shown in Table 1. This example assumes a practical but hypothetical example where the designer has been requested to design a house with 200 m^2 of living space (single-storey of 200 m^2 footprint or two-storeys of 100 m^2 each) in Edmonton, Alberta, Canada (HDD65 9495 days). The southern perimeter has to be a minimum of 25%, with a minimum of 50 m^2 of total window areas (could be translated into a wall-to-fenestration ratio), and a ceiling height of 3.05 m. A basement is also assumed to be desired along with an air tightness of 0.2 ACH. With those constraints, the optimization algorithm outputs the mathematically optimal combination of wall, and attic insulation (U-values), window U-value (constrained between 1.5 and 1.2 W/m^2.K) and window SHGC (constrained between 0.2 and 0.4). Naturally the optimization is a mathematical one, where the designer would then use that solution as a starting point to refine the design. The mathematical results along with some practical modifications to the inputs are shown in Table 1 below.

Table 1. Optimization calculation using the PLS model as a design starting point.

	OPTIMAL CALCULATIONS	**PRACTICAL DESIGN**
HDD65	8,998	9,495
FOOTPRINT AREA	100	100
NUMBER OF STOREYS	1.68	2
PERCENTAGE OF PERIMETER FACING SOUTH	25%	25%
BASEMENTS	0.79	1
CEILING HEIGHT	3.01 m	3.05 m
WALL U-VALUE	0.42 W/m^2.K	0.2366 W/m^2.K
ATTIC U-VALUE	0.27 W/m^2.K	0.1420 W/m^2.K
WINDOW U-VALUE	1.2 W/m^2.K	1.2 W/m^2.K
WINDOW SHGC	0.37	0.37
TOTAL AREA OF WINDOWS	50 m^2	50 m^2
SOUTH FAÇADE AREA	46.46 m^2	46.46 m^2
AIR INFILTRATION	0.235 at atm.	0.2 ACH at atm.
ENERGY CONSUMPTION	32,274 kWh	32,468 kWh
COST ANALOGUE	270 units	1837 units

It is worth noting that the algorithm reduced the amount of insulation required to the maximum in order to reduce costs, demonstrating that the balance of other requirements can offset costs. In an actual design example, the model would be further constrained by the lot shape and size, regulatory requirements, building and energy codes, etc.

3.3 Example 1 - Design of a Single-Storey 200 m^2 House (Hypothetical)

In this first example, a 200 m^2 house is being designed in Toronto, Ontario. It is assumed that that the designer is making a decision between using a wall U-value of 0.2366 $W/m^2.K$ and 0.2103 $W/m^2.K$. Using the simplified tool (example shown in Figure 12).

As the baseline design the following inputs were used:

- HDD65 is 7,120 days for Toronto
- Footprint Area is 200 m^2
- Single-Storey House
- Percentage of Perimeter Facing South is 22.2%
- Basement foundation
- Ceiling Height is 3.05 m
- Wall U-value is 0.2366 $W/m^2.K$
- Attic U-value is 0.26 $W/m^2.K$
- Window U-value is 1.5 W/ $m^2.K$
- Window SHGC is 0.3
- Total Area of Windows is 70 m^2
- South Façade Area 70 m^2
- Air Infiltration is 0.25 ACH at atmospheric

For such a house, the model estimates an energy consumption 52,575 kWh and a cost analogue for insulation of 1,866 units. The absolute values of these units are not meaningful, as they are heavily limited by the model scope and assumptions discussed in more detail in Section 4. The designer changes the Wall U-value to 0.2103 $W/m^2.K$ and the model estimates an energy consumption of 52,258 kWh and a cost analogue of 1,973 units. This means that a 0.6% decrease in energy consumption through adding wall insulation would result in a 5.7% increase in cost analogue. Whatever the goals of the designer may be, this decision-making tool provides valuable data that may not be easily quantifiable otherwise into the decision-making process, as well as being able to easily communicate a message to the owner, policy maker, or other decision maker.

The designer may consider the alternative to improve air-tightness of the house by about 4%, which is practically negligible, to incur the same benefit or reduction in energy consumption. The assumption being that this improvement in air tightness is more cost effective than the addition of insulation. This model does not capture the cost increase of the increased air tightness, but future versions perceivably could, and the decision can be made quite quickly.

3.4 Example 2 – Retrofit Design of a Two-Storey 150 m^2 House (Hypothetical)

Using the same base house for Example 1 as an existing structure where the owner/regulator is trying to decide what retrofit option to choose, assuming a limited budget. To limit the options for the purposes of this discussion, three possibilities are considered: (1) decrease the wall U-value (add insulation), (2) decrease the attic U-value (add insulation), and (3) replace the windows with a lower U-value window. For options (1) and (2) the model can calculate a cost analogue, however the model in its current state cannot calculate the cost analogue for windows, therefore it is assumed that the cost of installing new windows would be equivalent to the cost of adding insulation to the wall. It is also assumed that replacing the windows would improve air tightness of the house by 5%. Note that it is also assumed here that the existing windows are in good condition and do not need to be replaced.

The results for the different options using the simplified model shown in Figure 12 are shown in the Table 2 below.

Table 2. Options analysis for retrofit program.

	Baseline	**Option 1**	**Option 2**	**Option 3**
Wall U-value	0.2366	0.18	0.2366	0.2366
Attic U-value	0.26	0.26	0.188	0.26
Window U-value	1.5	1.5	1.5	1.2
Window SHGC	0.3	0.3	0.3	0.3
Air Infiltration	0.25	0.25	0.25	0.24
Energy Savings	-	~1%	~10%	~1.5%
Cost Units	-	231 units	228 units	231 units

Note that this allows the designer to understand that for approximately the same cost, the most significant improvement comes from increasing the attic insulation, whereas if the analysis was done by trying to understand the incremental improvement per unit U-value, the conclusion would be different. By including a cost component, the decision can be made with quantitative information. The same approach could be used by regulators by establishing a percentage improvement required (possibly for a certain cost budget) and then the designer using the same tool can achieve those targets using various combinations.

4. Model development and evolution

This model was designed to serve as an example for a framework of one possibility on how energy consumption design and regulation can be exercised without the need for complex and impractical models, especially when multiple combinations of factors are desired. Having said that, in the evolution of this model, it would be desired to:

1. Improve the accuracy of the model calculation by including higher order interactions, higher orders and other transformations of the factors, and additional factors as needed for the specific application. To achieve these goals, a larger dataset (preferably well-designed dataset) is the starting point on what would be required.
2. Increase the scope of the model inputs simply by increasing the variation in the input data to allow for a broader scope of applications.
3. Increase the scope of the model outputs: (a) an improved calculation of costs that include as many of the inputs as possible, (b) include peak load demand shaving which is becoming increasingly important, (c) include greenhouse gas emissions, and (d) include embodied energy of the material used.
4. Apply machine learning algorithms to continuously improve the model as well as potentially to incrementally allow for the inclusion of new technological innovations (current examples would be smart shading systems, demand response systems, etc.) to be able to advance the field simultaneous with the advancement of technologies.

5. Conclusions

In conclusion, this study recommends and demonstrates that it is beneficial and practical to utilize the power stochastic approaches for the design and regulation of energy efficiency of buildings. In the study, advanced analytics and statistics were leveraged to develop a framework of development for practical design models that should be used for the design process and regulatory process. In particular, by foregoing the urge to try to replicate a BPS model by using black-box statistical methods, and applying a PLS algorithm to develop the model whose non-black-box approach allowed for the use of the model in various practical ways to achieve the desired goals. These goals included a direct analysis of cost versus design decisions for new and existing housing, utilize linear programming (optimization) algorithms to mathematically calculate a global optimal design for energy consumption and cost, and a potentially the development and application of regulation, labelling programs, and incentive programs. Tools developed under the proposed framework could advance the field beyond the research and niche projects to become a mainstream design consideration. Further evolution of this model could also be used under the same framework to include a broader scope of environmental, social, and economic impacts.

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Chapter 7 – Summary & Conclusion

This chapter provides the key contributions, findings, and suggested continuation of the work as uncovered during the research work.

7.1 Summary of Contributions

The key contributions of this thesis and underlying research can be summarized as follows:

1. Definition and creation of a clear and precise framework and methodology to scientifically, objectively, and practically measure sustainability of any building, demonstrated through a prototype for single-family detached housing. The metric is the Sustainability Performance Metric (SPM).
2. Identification and confirmation of the need for a holistic metric for measuring sustainability to ensure truly sustainable designs are achieved.
3. Definition and creation of a new Building Envelope Coefficient of Performance (BECOP) which captures the energy efficiency of the building envelope in a manner that allows the designer to ensure compatibility with other aspects and components of buildings.
4. Identification and confirmation of the need for a building envelope efficiency metric established relative to a fixed datum to ensure truly efficient designs are achieved.
5. Definition of a clear and precise framework and methodology for a decision-making model and tool to practically consider costs and energy consumption simultaneously, leading to optimal designs as demonstrated via a prototype for single-family detached housing.

7.2 Conclusion

The key findings of the research are summarized as follows:

1. The industry programs commonly used to assess sustainability of buildings, such as LEED, BREEAM, and DGNB, are successful at achieving their goals of increasing market awareness and market value of sustainable practices, however they are not suitable to be used as metrics for measuring sustainability.

2. There are several academic methods presented in literature to measure sustainability or parts of sustainability, however their challenge is to measure and/or aggregate the various impacts of sustainability without subjective inputs such as weights.
3. LCA and LCC are measures that cover a wide range of ecological impacts and one aspect of economic impacts; however, they are not practical to be used as a decision-making tool.
4. The SPM framework was presented and developed as applicable to a wide range of human activities, including the built environment, using a balanced set of objective and function statements for environmental, social, and economic constraints.
5. The SPM was developed, applied and tested on detached single-family housing based on the strengths of the PLS algorithm. The SPM logic was demonstrated to be viable, practical, and realistic way to scientifically measure sustainable performance ensuring all three prongs of sustainability are given equal weight.
6. The SPM was shown to be a necessity to ensure that designs that intend to be sustainable are truly sustainable. Without a metric to measure sustainability, designs that rely on current methods are likely to be less sustainable, less economical, and disregard social impacts. As such, the development of the SPM using the presented framework is necessary, important, and powerful.
7. The BECOP metric developed to measure the efficiency of the building envelope provides a viable alternative to other metrics currently in use. As a result of the fixed datum or reference employed, the BECOP allows for interpretability in a similar manner to efficiency which allows comparison and compatibility with other systems (e.g. HVAC systems), ability to consider system performance, and its ability to identify opportunities for improved performance.
8. The need for a decision-making tool that can be used by building designers early in the process to feasibly investigate several options is demonstrated.
9. A practical and simultaneous energy consumption model or decision-making model that includes cost considerations is developed with a relatively small dataset using PLS algorithms. The linear nature of the PLS model would also allow for practical linear programming (optimization) to find a globally optimal design, optimizing for costs and energy consumption simultaneously.

10. Metrics for energy consumption that can be used for specification, performance requirements, are developed. Their need is clear in the mainstream industry to guide designers, owners, and regulators alike.

7.3 Suggestions for Future Work

The approach used in this research work is first of a kind in its field, and several challenges and areas where knowledge is not yet available are uncovered. To measure sustainability adequately, a PLS model has been shown to be a requirement as per the suggested framework.

The methods used to calculate the various impacts could be improved and designed specifically for the purpose of being included as one part of sustainability. In particular methods for calculating economic and social indicators. The calculation methods should be designed to use inputs that are practical and known by the designer in order to estimate those impacts. The development of such methods, and improvements of existing methods, would improve the data quality and subsequent models, tools and metrics. From that, it is reasonable to suggest that the creation or collection of larger datasets would become increasingly important, increasing the number of inputs, output (impacts), and observations (datapoints) that are included and accounted for by the SPM metric.

Among the additional aspects that would be desirable to measure, parameters that describe resiliency need to be captured. The concept of including resiliency as a phase of the life-cycle could be applied. As an initial step, only a small subset of resilient performance would be measured (e.g. fire, flood and flexibility in change of use) and included in the SPM. This would be made possible with larger datasets and improved tools for estimating various impacts. An additional improvement that would be required to the tools for estimating the impacts while building the datasets would be to ameliorate the ability of such tools to capture the nuances of the various levels of prefabrication and off-site construction.

Finally, this framework and methodology described within this thesis is conducive to supervised classification and machine learning algorithms, and investigating this option would be recommended future work. While investigating that, it is also recommended to investigate data analytic techniques other than PLS such as ANN. This is only feasible if larger datasets become available.

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