A Framework for Multi-Criteria Lifecycle Assessment of Building Systems in the Construction Industry

by

Samer Bu Hamdan

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Construction Engineering and Management

Department of Civil and Environmental Engineering
University of Alberta

© Samer Bu Hamdan, 2018

ABSTRACT

The increasing awareness of the sustainable implications of the construction industry requires an expansion in the types of assessment criteria used to evaluate the systems deployed in building. This expansion allows engineers to consider several criteria of various natures (e.g., economic and environmental) in the process of evaluating the viability of the developed solutions for building systems. Furthermore, the increasing demand for quality pertaining to the products of the construction industry necessitates greater integration in the development of the design of building systems. This implies the need to consider the interactions among building systems and the influence of these interactions on the potential technical performance of such systems during operations. The research presented in this thesis proposes a framework that accounts for (1) multiple criteria design assessment of building systems and (2) the interdependence among building systems to provide a decision support tool that ensures, at an early phase, a reduction in the impact of the end-product on the lifecycle cost, energy consumption, and CO_2 emissions of a building. This research also presents two case studies to illustrate the application of this framework during the design phase.

Tools that visualize the impact of building systems on value, such as cost, are common, but little attention has been given to visualize the collective contribution of the building systems to multiple values. This research proposes a visualization framework to bridge the gap in the practice of design visualization regarding the number of visualized criteria, visualizing throughout the entire lifecycle of the building, and achieving visualization that is concurrent with the design development. A case study is presented to demonstrate the application of the framework accounting for the lifecycle cost, energy consumption, CO_2 emissions.

DEDICATION

To my mother, Sawsan Danaf

For the love, trust, and continuous support throughout this long journey!

ACKNOWLEDGEMENTS

As this chapter of my life comes to an end, amid the surge of feelings, I can't but remember all those who were part of this milestone of my life.

Starting with Dr. Mohamed Al-Hussein, to whom I would like to express my profound gratitude for his continuous support and guidance, for his tolerance and understanding, for his mentoring and trust, and above all for believing in me and giving me the chance to achieve a long dreamed-of goal.

To my other supervisor, Dr. Ahmed Bouferguene, I would like to acknowledge all the long hours that he spent helping to shape this research and fine-tune its outcomes. I'd like to thank him for his patience and for all the ideas he shared, cultivated, and helped to harvest.

I always consider myself lucky for the good friends life brings me, and I wouldn't find a better chance to express how grateful I am that you are part of my life in its bitterness and sweetness. Ziad, Beda, Aladdin, Regina, Hussein: Thank you for being a family for me.

Claire and Jon, thank you for all the support, advice, collaboration, patience, and friendship you have provided.

I also would like to thank the greater research group for the time spent exchanging ideas and sharing knowledge.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF APPREVIATIONS

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

BIM: Building Information Modelling

BIMs: Building Information Models

CBS: Criteria breakdown structure

CMYK: Cyan-Magenta-Yellow-Black Colour System

GFI: Ground Fault Circuit Interrupter

HBM: Heat Balance Method

HoQ: House of Quality

HSL: Hue, Saturation, and Luminance Colour System

HVAC: Heating, Ventilation, and Air Conditioning

LC: Lean Construction

LCA: Lifecyle Assessment

LED: Light-emitting Diode

LPS: Lean Production System

MAUF: Multi Attribute Utility Theory

MCLCA: Multi-criteria Lifecycle Assessment

MCUF: Multi-criteria Utility Function

MDF: Medium-density Fibreboard

MOO: Multi-objective optimization

MRL: Mean Residual Life

MTTF: Mean Time To Failure

O.C.: On Centre

PSS: Product-service Systems

QFD: Quality Function Deployment

REPA: The Resource Environmental Profile Analysis

RGB: Red-Green-Blue Colour System

S-LCA: Social Life Cycle Assessment

TC: Target Costing

TPS: Toyota Production System

TVD: Target Value Design

VA: Value Analysis

VC: Value Control

VDD: Value-driven Design

VE: Value Engineering

VM: Value Improvement

VM: Value Management

VM: Visualization Matrix

VP: Value Planning

VR: Value Research

WBS: Work Break-down Structure

WWR: Window-to-Wall Ratio

GLOSSORY OF TERMS

Architectural programming: the process of defining and documenting the client's needs and expectations of the building to be designed. Architectural programming output defines the functional and geometrical requirements of the building.

Value: the goodness of design desired by people. The word value(s) in the present research refers to one or all of the following: cost, energy consumption, and CO_2 emission assessed over the lifecycle of the building.

Assessment criteria: the set of values the design is driven to fulfill. In this research, this set includes cost, energy consumption, and CO_2 emission assessed over the lifecycle of the building.

(Note that value(s) and assessment criteria are used in this research to refer to cost, energy consumption, and CO_2 emission assessed over the lifecycle of the building. However, while the word value(s) is used in general, assessment criteria is used to describe cost, energy consumption and CO_2 emission when they are used as boundaries for the design process.)

Objective-oriented design: the process of driving the design to fulfill one of several criteria that are not included in the architectural program, such as cost, time to construct, environmental impact, etc.

Value-adding: is the process of improving a product or service prior to its release to the end user. This improvement can be a reduced price, lower environmental impact, longer lifespan, etc.

Technical performance of a system: is how the system functions during the operational phase of a building.

“*Everyone designs who devises courses of action aimed at changing existing situations into preferred ones*.”

– Herbert Simon

1. INTRODUCTION

1.1. Background and Motivation

Following the 2015 United Nations Climate Change Conference held in Paris, many governments around the world have begun to introduce legislation to improve their environmental practices, including the provincial government of Alberta, e.g., the new Carbon Tax (Alberta Climate Leadership Plan 2016). It is significant to note that the construction industry contributes nearly 12% of the total CO_2 emissions in Canada (during the construction and operation phases of buildings) (Statistics Canada 2012). Therefore, any sustainable solution must consider the construction industry. In addition to its harmful impact on the environment, the construction industry is sensitive to political changes and economic trends (Berman and Pfleeger 1997). In this environment of economic downturns, competition, and the pressure to adopt more sustainable policies, construction industry stakeholders are required to improve their processes in order to achieve better performance, remain competitive, and address the increasing demands from clients. Therefore, several frameworks have been developed to connect customer demands with the deliverables of the construction industry, such as Lean Construction and Value Engineering. However, construction practitioners often overlook the similarities of such methods, which may hinder communication and shared understanding of the best practices of each method. Therefore, it is important to develop a common understanding pertaining to the predominant methods that drive design to meet certain criteria in the construction industry in order to improve communication among stakeholders. It is also vital to list the key features required for the success of aligning the design outcomes with a set of assessment criteria in order to allow for further enhancement in this practice in the construction industry.

The multi-disciplinary nature of the construction industry adds a layer of complexity to the design process represented in the interdependencies within the building. Accounting for the interdependencies amongst the various components that exist in a building requires the adoption of a holistic design approach. Such an approach underscores the effect of design decisions on the performance during operation, and ensures the required value is delivered at the commissioning of the project. This exercise is not supported in the traditional practice of design in the construction industry, where, despite the broad consensus on the importance of integration, designers tend to work in silos. This method of working in seclusion implies the practice of solely evaluating the impact of design decisions on a system and overlooking the impact on other disciplines (e.g., the selection of wall R-value, which occurs during the design of the building envelope, affects the performance of the heating system that is selected and designed as part of the mechanical system.) Therefore, the research presented in this thesis proposes the development of a framework that can be used to evaluate the design against multiple criteria (i.e., cost, energy consumption, and CO_2 emissions) by quantifying the interactions between the components of a building. In doing so, the designers, although in practice are likely to work in silos, can receive feedback in regard to the end-product and are provided with an opportunity to revise their solutions. In other words, this contribution provides an ad hoc approach to global optimization of design in the construction industry, since it allows designers to understand the global impact of their decisions and by the same token provides additional information to the customer. This approach can, therefore, improve the channels of communication among all stakeholders involved in a project.

Furthermore, the absence of proper tools for communicating and interpreting value considerably hinders the broad and proper implementation of the framework proposed in Chapter 3, as evidenced by the practices of other industries. Therefore, in the present research a framework is developed on the premise of bridging the gap in the construction industry regarding value visualization (i.e., visualising the interactions between building components and cost, energy consumption, and CO_2 emissions). It provides a practical and easy-to-use tool by which each element in a building (e.g., columns, windows, doors, etc.) is assigned a unique appearance that represents its collective contribution to the previously mentioned values.

1.2. Research Objectives

The goal of the present research is to improve the construction industry practice in regard to driving the design to fulfill multiple criteria assessed throughout the lifecycle of a building, wherein the deliverables of the design phase increase the likelihood of meeting client expectations. It also aims to incorporate the performance of systems in a building as a metric of evaluating the design, thereby increasing both the performance and the compatibility of the building systems. Therefore, the research presented in this thesis is built upon the following hypothesis:

"Incorporating the interdependencies of building systems during the design phase will increase the potential technical performance of the building as a whole and reduce the lifecycle cost, energy consumption, and CO_2 emissions of the building."

Furthermore, this research encompasses the following objectives.

1. Define the interdependencies among building systems and the assessment criteria.
2. Select a model for representing the technical performance of building systems throughout the lifecycle of the studied building.

3. Define the interdependencies among building systems themselves through the study of the influence of building systems on the technical performance of one another.
4. Develop a multi-criteria lifecycle assessment framework that accounts for the interdependencies among system components and the effects of the assessment criteria on the technical performance of building systems.

5. Develop a visualization framework to improve assessment criteria (i.e., lifecycle cost, energy consumption, and CO_2 emissions) communications and interpretations that support the multi-criteria lifecycle assessment design effort.

The developed approaches in the present research together serve as a decision-support tool that ensures at an early phase that the end-product meets stakeholder requirements in terms of the selected assessment criteria (i.e., lifecycle cost, energy consumption, and CO_2 emissions), while at the same time ensuring that the building systems reach near-optimal performance as one holistic system.

1.3. Organization of the Thesis

The thesis includes five chapters as follows:

Chapter 1: Introduction. The current chapter introduces the concept of the research, identifies the objectives, and presents the layout of the thesis.

Chapter 2: Literature Review. This chapter scrutinized the various criteria-driven assessment methods used in the construction industry in terms of origins, fundamental principles, and limitations. It then explores the practice of value-visualization in the construction industry to support the endeavors of developing a framework for value visualization. Chapter 2 also discusses several theories and tools used in this research, chiefly Reliability Theory, Quality Function Deployment, and Utility Theory.

Chapter 3: Methodology. In Chapter 3, the methodologies that underscore the development processes are presented.

Chapter 4: Case Studies. This chapter presents numerical examples for the application of the proposed frameworks.

Chapter 5: Conclusion and Future Research. Chapter 5 summarizes the findings of the research, lists it contribution, and recommends future developments.

2. LITERATURE REVIEW

The literature review of the present research is divided into two parts. The first part seeks to review the state-of-the-art literature in order to define the gaps that need to be addressed by the present research study. This part explores the literature pertaining to the value-adding practices (i.e., the processes of improving a product or service prior to its release to the end user. This improvement can be a reduced price, lower environmental impact, a longer lifespan, etc.) in the construction industry with the goal of defining areas of improvement in these practices. The first part of the literature review then investigates the practice of value-visualization in the construction industry. The second part of the literature review provides background information pertaining to the tools and concepts used in the present research and how these tools are utilized. This part addresses reliability theory, quality function deployment, and utility theory.

2.1. State-of-the-art literature

2.1.1 Value-adding Methods in the Construction Industry

2.1.1.1. Introduction

Value can be defined as goodness people desire (Hart 1971; Schwartz 2007; Schroeder 2016), thus the manifestation of this abstract concept in a physical product is a rather sophisticated process.

Therefore, all industries, including the construction industry, demand the existence of frameworks that translate the desired value into deliverables. The predominantly-used value adding frameworks in current construction practice are adaptations from other industries (e.g., Lean, Value Engineering); however, there is a tendency among construction practitioners to change the names of adopted tools (e.g., Target Costing became Target Value Design), which creates a false impression that practitioners are dealing with different approaches. These terminological changes create discontinuity in knowledge transfer, which can confound the efforts of researchers aiming to leverage the developed frameworks (Chwe 2013). There is thus a need for mutual assimilation between differing frameworks for the fundamentals of value-adding, such that practitioners can ascertain a firm basis for evaluation and practice. When the fundamentals, limitations, and practices of value-adding frameworks are well understood, it is then possible to define the issues that need to be tackled in order to overcome the deficiencies of existing value-adding frameworks. The construction industry is then well-positioned to continue to deliver value to its stakeholders. Therefore, this section examines and clarifies the origins, principles, and limitations of the following value-adding frameworks: Value Engineering, Lean Construction, Target Costing, Target Value Design (as the relevant literature indicates that these methods are widely used in the construction industry), Value-Driven Design, and Lifecycle Assessment. The establishment of a common understanding of these value-adding methods is based upon an extensive and comprehensive review of the literature in construction and manufacturing in order to define the principles and limitations of each framework.

2.1.1.2. Value Engineering (VE)

Value engineering originated shortly after WWII, driven by the shortage of supplies during and following the war and the resulting need for lower prices. Lawrence D. Miles (then an engineer at General Electric) proposed a systematic approach for problem-solving to reduce unnecessary costs, which he called Value Analysis (VA). Miles defined VA as “a complete system for identifying and dealing with the factors that cause unnecessary cost or effort in products, processes, or services” (Miles 1961). Due to the success this method achieved in reducing costs, the U.S. Department of Defense adopted it into practice in 1954 (Dell'Isola 1974), changing the name to Value Engineering (VE) as proposed by Admiral Wilson D. Leggett (Fowler 1990).

Hinging upon the efforts of Alfonse Dell'Isola, the construction industry began an aggressive implementation of VE in the early 1960s (Fowler 1990). Since then, the method has been given many names corresponding to implementation in different contexts, such as value control (VC), value improvement (VI), value management (VM), value planning (VP), and value research (VR) (Dell'Isola 1974; Fowler 1990; Parker 1985).

Principally, VE is an objective-oriented approach that aligns the design process with desired values set by stakeholders (ASTME 1967). This objectivity is achieved through the fundamental concepts that characterize the implementation process. These fundamentals are as follows:

- Function: describes the utilization of the developed product, service, or process, thereby defining the goal of performing VE. The functions are, in fact, the "fundamental skeletal" of the entire approach, regardless of the application area (U.S. Department of Defense 1983).
- Worth: the minimum monetary value needed to deliver a certain function. It should be noted that "worth" is independent from the "cost" associated with the failure caused by a certain element. For instance, the failure of a pad footing may cause the failure of the building. However, the worth of that pad footing is the minimum cost paid to construct it.
- Cost: the total monetary value needed for a certain function, which includes the cost of production/construction and operation, and can be extended to the cost of replacement. Notably, VE considers the lifecycle cost of the function, rather than looking only at the cost of manufacturing or construction (Miles 1961; Dell'Isola 1974; Public Buildings Service 1992; NEDA 2009).
- Value: the relationship between the worth and the cost of a given function. Value can be expressed as Equation 2-1 (U.S. Department of Defense 1986).

$$Value = \frac{Worth}{Cost} \tag{2-1}$$

VE aims to reach the lowest possible cost that still satisfies the requirements of the end user, as expressed in Equation (2-1). This implies eliminating as much waste as possible (as identified by Miles (1961), there are 8 types of waste) from the process in order to reduce the cost and increase the worth, and, in turn, the value. This leads to the common misconception surrounding VE in this regard, which is that it is concerned with reducing the cost of deliverables (Dell'Isola 1974). In fact, according to the value function as defined by Mudge (1971), Fowler (1990), and Fowler (1990), and as expressed in Equation (2-2), VE incorporates the functionality and quality of the end deliverable along with cost reduction.

$$Value = \frac{user's\ initial\ impression + satisfaction\ in\ use}{first\ cost + follow - on\ cost} \tag{2-2}$$

Furthermore, VE involves some essential practices for decision making that could be considered key principles (U.S. Department of Transportation 1997; WVDOH 2004): (1) cross-functional team work, which implicitly requires proper communication among project participants; and (2) continuous resolution of any issues arising until the final deliverable is ready (Miles 1961; Mudge 1971; U.S. Department of Transportation 1997; WVDOH 2004).

Notably, the primary critique for VE is a lack of standardization, as several researchers refer to the same concept using different classifications. For example, while function, worth, cost, and value are considered fundamental to VE (Miles 1961; U.S. Army Management Engineering Training Activity 1983; Fowler 1990; U.S. Army Management Engineering Training Activity 1983; Fowler 1990), NEDA (2009) does not clearly classify these concepts as fundamental principles of VE. Rather, it discusses "Job Plan"[1] under "VE fundamentals". This claim is also supported by Maniak et al. (2014), who argue that the traditional practice of VE does little to assist in the clear definition of value in exploration projects, which, despite defining the functional attributes and following a logical approach to maximize value in the product, fails to satisfy the expectations. The lack of a structured framework is the major cause of this failure (Maniak et al. 2014). Furthermore, while VE supports the intuitive determination of value, it does not support further processes such as design and performance optimization (Soban et al. 2012). Fong (2004) lists four major drawbacks that hinder the proper implementation of VE and therefore diminish its potential benefits:

- in application, there is a discrepancy in the definition of value among clients and VE practitioners;
- in education, there are insufficient training programs, materials, and educators;
- in research, there are inadequate research activities and funding; and
- there is a gap between university research and the application of VE.

As can be observed, despite the success achieved by VE, the lack of a well-defined structure for implementation, the absence of clear procedures to define value, and the little support it provides to design efforts are the primary drawbacks associated with the implementation of VE.

2.1.1.3. Lean Production System (LPS) and Lean Construction

Acknowledging the importance of remaining competitive with America to ensure the survival of the automobile industry of Japan marked the dawn of the Toyota Production System (TPS)

[1] "A systematic and organized plan of action for conducting a VE analysis and assuring the implementation of the recommendations" (U.S. Department of Transportation 2015).

(Ohno 1988)[2]. To achieve this, Taiichi Ohno, the father of TPS (Sugimori et al. 1977), began by identifying and eliminating various forms of process waste in the production line. This effort culminated in the introduction of Just-In-Time: feeding the process flow with the exact number of parts at the necessary time (Ohno 1988); and autonomation: focusing on automation while providing production line workers the opportunity to run and improve the production line (Sugimori et al. 1977), both of which became defining characteristics of the TPS (Ohno 1988). The improvements contributed by TPS to Toyota culminated in positioning the organization to become the most profitable automotive company in the world with a market capitalization of US$184.8 billion (The New York Times 2017). The high level of competitiveness achieved by Japanese companies due to the application of TPS concepts attracted global interest and the name "Lean" was coined by John F. Krafcik, which emphasizes the core principle of TPS in reducing waste (Staats et al. 2011). Lean principles have since been implemented in many aspects of modern life, including education (Emiliani et al. 2005), health care (Mazzocato et al. 2010), the service industry (Kanakana 2013), and the construction industry (Koskela 1992).

Despite the varying characteristics of the manufacturing and construction industries, pioneer researchers began to explore the adoption of lean thinking in construction in the late 1980s (Howell 1999). In 1992, Koskela presented his research on considering workflow holistically when studying individual construction activities to reduce the process waste associated with then-current construction management methods (Koskela 1992). The development of a planning system for construction that accounts for the principles of the lean production system (LPS) began in 1992 (Ballard 2000), and the formal introduction of this system, i.e., Last Planner®, in

[2] To incite his employees to find innovative solutions to improve productivity, Toyoda Tiichiro (1895–1952), then the president of Toyota, said "Catch up with the Americans in three years. Otherwise the automobile industry of Japan will not survive".

academia occurred shortly after at the inaugural *Conference of the International Group of Lean Production* (Ballard 1993). The late 1990s introduced the establishment of the Lean Construction Institute, which was the result of collaboration between Glenn Ballard and Greg Howell (Ballard 2000) "to develop and disseminate new knowledge regarding the management of work in projects" (Lean Construction Institute 2016). Henceforth, lean construction drew considerable attention among construction practitioners, with a recent report published by McGraw Hill confirming that 43% of those surveyed indicated that they have implemented lean construction in practice (McGraw Hill Construction 2013).

TPS is "based fundamentally on the absolute elimination of waste", where 7 types of waste are defined through the application of just-in-time and autonomation (Ohno 1988). Furthermore, as producers strive to reduce cost (by reducing waste), they must still deliver reliable and value-rich products that will ensure the competitive position of the company in the market, as stated by Ohno (1988). Womack and Jones (2010), on the other hand, define the principles of LPS in a different manner, where they provide a systematic method of application. In their book, *Lean Thinking*, the authors consider that lean thinking defines value from the customer perspective (Specify Value), then orders the corresponding value-adding task (Identify the Value Stream). Next, the task is performed continuously whenever needed (Flow and Pull), which ultimately ensures increasing efficiency (Perfection) (Womack and Jones 2010).
Alternatively, Staats et al. (2011) argue based on a study by Hopp and Spearman (2004) that Ohno (1988) elaborates on the philosophical aspects of Lean Theory, but fails to provide a detailed account, whereas Womack et al. (1990) provide useful examples without giving clear definitions of concepts. Therefore, Staats et al. (2011) conclude that the principles proposed by Spear and Bowen (1999) bridge the gap between those proposed by Ohno (1988) and Womack

et al. (1990). Spear and Bowen (1999) present the principles of TPS, through four rules followed in the Toyota plants. Table 2-1 presents these rules and the principles they embody.

Table 2-1 LPS rules and embodied principles adapted from Spear and Bowen (1999)

Rules	Embodied Principle
Rule 1: "How People Work"	Activity definition
Rule 2: "How People Connect"	Requirements and responsibilities are defined and communicated
Rule 3: "How the Production Line is Constructed"	Simplified, stable design for the production line that guarantees the flow
Rule 4: "How to Improve"	Create a systematic approach for problem-solving that consistently encourages people to improve

To facilitate the adoption of LPS concepts, the construction industry underwent a reformation on the conceptual level, such that construction activities can be understood as a single workflow distributed across a finite number of stations, and ultimately that concept of production theory can be applied in construction (Koskela 1992; Ballard 1999; Howell 1999). Koskela (1997) summarizes the principles underlying the application of lean production in construction as follows.

- Reduce waste by eliminating non-value-adding tasks.
- Systematically assess the requirements of customers to enhance the delivered value.
- Increase stability by reducing the likelihood of changes (Howell and Koskela 2000).
- Decrease the time required for performing tasks.
- Reduce complexity by reducing the variability (Jensen et al. 2009).
- Enhance the flexibility of deliverables (whether tools or end-product) with the aim that any developed deliverable should accommodate as many needs as possible with minimal or no change.
- Improve transparency.

- Maintain the focus of the control process on the finished tasks.
- Continuously improve the processes.
- Achieve balance in flow and conversion.
- "Benchmark".

It is important to note that whether in LPS or lean construction the main goal is to eliminate as much waste as possible from the process of production/construction. Also, both consider the customer/client as the source of the value that the process should maximize, and the final deliverable must fulfill.

Throughout its years of implementation, LPS has been scrutinized by numerous observers. According to Anvari et al. (2011), ambiguous and inconsistent customer definitions of values can limit the effectiveness of LPS. Furthermore, Chicksand and Cox (2005) argue that the application of lean thinking in the supply chain may lead to a dependency on fluctuating customer demand, which can have a negative effect on the producer. For instance, LPS considers stored materials as a waste that needs to be minimized. As such, procurement of new materials to produce the end-product is linked directly with a purchase order placed by a customer. While this practice helps to streamline the production line and reduces the resources that need to be acquired, handled, and stored, it does not take into consideration the external factors affecting the material suppliers. On one hand, any shortage in the required building materials can cause a slowing or even a complete shutdown of the production line; on the other hand, the minimized stored material makes the end-product cost subject to any fluctuation in the cost of required building materials, and it also negates any potential cost savings realized from acquiring and storing materials during any market-driven drops in the cost of these materials (Cusumano 1994). Based on the presented literature regarding LPS and lean construction (LC), it should be noted that although they reduce waste and increase the efficiency of the production process, they pay little attention to the design phase.

2.1.1.4. Target Costing (TC) and Target Value Design (TVD)

Soon after WWII, due to the scarcity of resources, VE practitioners acknowledged the need to maximize the product attributes that were most important to consumers. Japanese companies adopted VE and its concepts in the early 1960s, at which time it was widely implemented in various industries (Fowler 1990). Japanese companies, chiefly Toyota, extended the VE concept (Gagne and Discenza 1995; Leahy 1998; Ansari et al. 2006) and named it "Genka Kikaku" (Nicolini et al. 2000; Feil et al. 2004). Genka Kikaku, expressed in English as Target Costing (TC), was then renamed Target Cost Management by the Japan Cost Society in 1995 (Feil et al. 2004). TC, it should be noted, can be defined as "a technique to strategically manage a company's future profits" (Cooper and Slagmulder 1999).

The adaptation of TC in the construction industry is called Target Value Design (TVD) (Zimina et al. 2012; P2SL 2017). TVD is a reverse approach that begins with setting a goal—usually the cost of the project—rather than beginning with the design (Helms et al. 2005). Proponents of lean construction argue that TVD has significantly reduced cost and improved the cost control process for construction (Ballard 2008; Ballard 2012; Reymard Savio Sampaio et al. 2016; Obi and Arif 2015; Oliva et al. 2017).

TC involves several key principles that constitute a systematic thinking approach to achieve the desired outcome (Ansari 1997; Ellram 2006; Everaert et al. 2006; Ax et al. 2008; Kato 1993). These key principles are summarized below.

1. Price-led costing: the cost of the product is a target of the design process. This target is determined based on the competitive market price and target profit as expressed in

Equation (2-3).

$$C = P - \pi \tag{2-3}$$

where C is the target cost, P is the competitive market price, and π is the target profit.

2. Focus on the customer: the requirements of the end users are an essential component in the design process. Designers must not compromise the desires of the customer in terms of quality, reliability, and low price in their efforts to lower the production cost.
3. Focus on design: TC philosophy is built on the notion of allotting more time to the design process, given that this is the phase that is the least costly and most influential on the total cost of the product. This notion is reflected in the following strategies representative of TC:
   - Manage costs before they are incurred.
   - Assess the impact of cost on the product.
   - Examine the design collaboratively and cross-functionally before it goes to production.
   - Embrace the concurrent, rather than sequential, development of the design.
4. TC is a cross-functionally oriented method: in TC the design is carried out using a cross-functional team that involves personnel from various departments of the organization(s) that contribute to the design and production. This allows the team to capture the various aspects that affect the design.
5. Lifecycle orientation: TC aims to reduce the cost of production throughout its entire lifecycle, including the deposition cost. TC considers the cost from the perspective of the user, and thus aims to reduce the operation and maintenance cost. It also focuses on reducing production cost, including deployment and marketing.

6. Value-chain involvement: TC considers all the parties involved in the process of creating value for the product, including suppliers and dealers, for example.
7. Continuous improvement: here the company strives for continuous improvement of the product until it reaches the targeted cost. The product should not be introduced to the market prior to the fulfillment of the target.

Ibusuki and Kaminski (2007) argue that VE and TC complement one another, as the former defines potential areas for cost reduction while the latter ensures the developed products comply with the strategic goals of the corporation. However, the authors view the costing aspect of TC as an algorithmic application of VE (Ibusuki and Kaminski 2007). This characteristic enables practitioners to overcome one of the major disadvantages of VE, i.e., the lack of a systematic application approach.

Macomber et al. (2007), on the other hand, describe the foundation of TVD in nine points, as follows:

- Designers and clients should work closely and openly with one another throughout the design phase to clearly define value and streamline the design to satisfy the value.
- The team should come up with an innovative solution for design and construction.
- The design must be evaluated against a set budget, where the design is to be executed within this budget. *When budget matters, stick to the budget.*
- All stakeholders must be incorporated in the planning and re-planning of the project.
- The project should be designed in smaller batches, while developing a procedure to approve the overall design as it proceeds.
- The design process should be directed toward what stakeholders' value, and in the same sequence as it will be carried out. This will reduce rework.

- A small design group should be maintained.
- Design should be carried out in large spaces to encourage team involvement.
- An assessment meeting should be held following the completion of each phase.

Despite the significant achievements of TC, Kee (2010) confirms that TC fails to incorporate the cost of capital into production-related decisions, and thus may not yield the best alternative in terms of economic considerations. Also, Kee (2013) argues that the utilization of TC is limited in products with interdependencies due to the complex interactions among the constituent components that influence the overall value of the end-product. Moreover, Gerst et al. (2001) observe that TC tends to give less consideration to the technical "realism"—that is, the technical attributes and performance—of the designed product.

Whereas the concept of value in TC may extend beyond the monetary value of the product or the service that is designed within the TC environment, the manner in which this method has been applied suggests that cost control is the principal benefit to be derived from its implementation (Dekker and Smidt 2003). The traditional practice of TC is based upon a pre-allocation of the maximum allowable cost over the different items in the cost breakdown structure (CBS), where designers strive to deliver designs within these constraints. This process thus focuses more on the managerial aspect than on the technical aspects and behaviours of systems (Bertoni et al. 2015). Everaert (1999) adds that TC requires more planning time compared to traditional cost reduction methods. To conclude, TC/TVD introduced an objective-oriented design approach which is not supported by either LPS or VE. However, this objective-oriented design falls short in accounting for the interdependencies among the product components, and therefore, fails to account for the technical performance of the resultant product.

2.1.1.5. Value-driven Design (VDD)

Implementing VE, LPS, and TC has enabled several branches of industry to expand and achieve considerable profit. Nevertheless, large-scale and highly complex projects continue to see cost overruns and schedule delays, which is partially attributable to overlooking technical performance during the design phase (Collopy and Hollingsworth 2011). In the late 1960s, Herbert Simon (see Simon (1996) for more information) considered that the problem of engineering design originates at the interface between the "internal structure" of a product and the external features that reflect the users' requirements (Cheung et al. 2012), underscoring the need to extend equal importance to user requirements (e.g., cost cap) and internal system requirements (e.g., compatibility among components). In the 1960s and 1970s, several researchers suggested adding value to the system design process through optimization and the application of utility theory in the design process (Collopy and Hollingsworth 2011; Cheung et al. 2012; Cheung et al. 2012). The work presented by Hazelrigg (1998) provided a strong basis for incorporating design theory into the design process, and established an initial framework for value-driven design, although the term itself was not coined until 2006 by James Struges (Collopy and Hollingsworth 2011). Value-driven design (VDD) can be described as an engineering-oriented method that focuses on the hardware of the various systems in order to deliver high overall performance while adding the value as a constraint in the design process (Bertoni et al. 2015; Soban et al. 2012).

The delivery of highly-performing hardware is an integral component of quality (Owlia and Aspinwall 1998), which VE, LPS, and TC strive to achieve. However, VDD researchers observe, as indicated by Collopy and Hollingsworth (2011) and Bertoni et al. (2015), that the traditional practice for adding value assigns higher priority to end user requirements than to optimizing the technical aspects of the designed systems. This tends to result in overlooking how the designed systems may be influenced by setting value constraints, such as cost, and eventually leads to lower system performance (Collopy and Hollingsworth 2011; Bertoni et al. 2015). Yet, VDD has not been widely acknowledged by the construction industry, although some researchers, such as Zhuang et al. (2017), have begun to explore its application in architectural design. However, until an integrated platform outlining how the components of building systems interact with one another is developed, VDD will continue to be under-utilized.

VDD focuses on the technical performance of the designed system as the primary metric for the evaluation among different alternatives (Bertoni et al. 2015). The skeleton of VDD is the “value model” that links the “economic” operational features of the product with its manufactured components (Cheung et al. 2012). To build the value model, VDD provides a sequential process described by Isaksson et al. (2013) as follows:

1. Define the needs of the customer (values) through focus groups, questionnaires, or any other method that can capture the user requirements and assign weights for these requirements/values.
2. Define the technical features and their boundaries.
3. Map the requirements with technical features by defining (a) the existence and degree of correlation, (b) the type of optimization problem, the satisfaction limits, and (c) the individual value.
4. Repeat Step 3 until the results are satisfactory.
5. Determine the overall value merited through the final design.

VDD is flexible in terms of the method used to evaluate the gained value (Isaksson et al. 2013), such as the Net Present Value (NPV) method (Collopy and Hollingsworth 2011; Cheung et al.

2012), and the multi-objective utility theory (Zhang et al. 2013), among others. Given that VDD maintains the core principles of VE, such as the value function, it extends the practicality of VE by providing a sequential methodology to incorporate value in the design process and link it with the engineering characteristics of the product.

Although VDD provides a systematic method that combines the technical performance of the system and value of a product (Isaksson et al. 2013), the monetary assessment of VDD limits its efficiency when it is used to evaluate other values such as "lifesaving" (Surendra et al. 2012). Soban et al. (2012) observe the transformation of the "intuitive" process of value definition into practical application (i.e., developing the value model) to be inherently challenging. Curran (2010) and Bertoni et al. (2015) consider that VDD focuses on performance as the driver of value rather than incorporating the customer requirements into the design process. In addition to critiques of the underlying theory, Curran (2010) points out that there are several inherent challenges in the application of VDD:

- evaluation of value is not straightforward;
- formulation of the objective function is not a simple task;
- optimization of the formulated objective function is not error free; and
- integration of all the components in the function is an undertaking which increases in complexity as the number of components increases.

Note that, as VDD bridges the gap in regard to accounting for the technical performance of the designed product and provides a design-assisting tool, it succeeds in prioritizing the performance over customer needs as the literature indicates.

2.1.1.6. Lifecyle Assessment (LCA)

As can be observed in the presented literature, the term "lifecycle" is used and affirmed in several value-adding methods, such as VE and TC, to indicate that cost should be assessed throughout all the phases of the product life, which is referred to as lifecycle cost. However, as the predominant value-adding approaches focus on the monetary value, amidst the increase of the environmental awareness in the late1960s and early 1970s, environmental specialist called for a systematic approach to assess the environmental impact of products (Guinee et al. 2010). The Resource Environmental Profile Analysis (REPA) reports represented the first step toward the development of a systematic approach of environmental impact assessment, which was used to assess the resource requirements and environmental load of beverage containers for the Coca Cola company (Horne et al. 2009). The REPA had undergone a conceptual development process between the years 1970 and 1990, which culminated into the development of Lifecycle Assessment (LCA), which also underwent a standardization process between 1990 and 2000, until the early 2000s when the International Standards Institute published a series of standards (i.e., ISO 14040 and ISO 14044) that regulates the application of LCA (Horne et al. 2009; Guinee et al. 2010). Therefore, from an environmental standpoint, LCA is a "compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle" (ISO 2006), and it is widely adopted by the industry and research community for environmental assessment due to the systematic framework it provides.

LCA has been utilized in the construction industry despite the difficulties associated with its application compared to other industries (Baribian et al. 2009; Sharma et. al. 2010; Buyle et al. 2013). Examples of this application can be found in the work of González and Nacarro (2005), who use LCA to reduce the emitted CO_2 by up to 30% during construction operations. Ribeiro et al. (2008), on the other hand, propose an engineering lifecycle assessment that combines the benefits of LCA in reducing the environmental impact and meeting the material strength requirements.

It is also important to note that assessing the environmental impact of the construction industry product is not performed solely using LCA. Several researchers have developed various approaches through which the environmental impact of construction tasks is assessed (Azhar et al. 2010; Wong and Kuan 2014; Govindan el al. 2016).

As indicated, the term lifecycle assessment is widely associated with the environmental assets of the studied product. The present research, however, is aligned with the work of value-adding practitioners, where LCA demonstrates the assessment of any value throughout the lifecycle of the designed product and not only the environmental measures.

2.1.1.7. Current Practice and General Discussion

Despite the achievements of the mentioned methods in regard to cost savings, their primary focus is on the economic aspect of projects (Miles 1961; Mudge 1971; Dell'Isola 1974; Dell'Isola 1966; Dell'Isola 1982; Kim and Lee 2010; Cheung et al. 2012). To address the gap that exists between cost and value considerations, researchers have developed frameworks to assess environmental aspects as part of the selection criteria during the planning of a construction project. For example, sustainable target value design has been developed to address the case in which stakeholders are concerned about the environmental impact of the project, rather than using traditional TVD for the assessment (Russell-Smith et al. 2015). Arroyo et al. (2015) make use of analytical hierarchy process (AHP) and choosing by advantage (CBA) methods with the aim of achieving synergy between TVD and sustainability. However, sustainability measures are still typically limited to waste reduction and minimization of carbon footprint (Novak 2012). Based on the previous discussion, it is important to develop a unified value-adding framework for the construction industry to improve communication among the various disciplines and parties involved in a construction project. This unified framework can ensure cross-disciplinary knowledge transfer among the stakeholders of a construction project. Consequently, it can contribute to improving the overall value of the project. This framework is defined by the following characteristics:

- flexible to accommodate multiple values (e.g., economic and environmental);
- efficient to deliver the multiple values throughout the various construction phases;
- able to accommodate all the shared principles of the various existing frameworks; and
- able to account for the interrelations among the various components of building systems.

The development of such a framework will assist in creating shared terminology among the involved parties in construction and will help to ensure the delivery of the value demanded by end users.

2.1.1.8. Defining the requirements of the multi-criteria lifecycle framework requirements

The discussion pertaining to the principles of value-adding methods currently used in the construction industry can be summarized in Table 2-2, drawing a comparison between the principles of the predominant value-adding method on the construction industry.

Table 2-2 Comparison of the principles of value-adding method in the construction industry

Principle	**VE**	**LPS/ LC**	**TC/ TVD**	**VDD**
Concurrent design			●	●
Simultaneous improvement	●	●	●	●

Maintain efficient communication within and outside of the team	●	●	●	●
Cross-functional team	●	●	●	●
Design focused			●	●
Lifecycle cost	●		●	●
Incorporate all involved parties	●	●	●	●
Value is interpreted as a function	●		●	●
Customer-oriented focus	●	●	●	
Performance-oriented focus				●
The single nature of considered value	●	●	●	●

The similarities among the predominant methods are apparent, although they are often overlooked by construction practitioners. Among the discussed value-adding methods, TC and VDD were developed primarily to support design operation. Therefore, their principles constitute a firm basis to build upon any improvement in the practice of value adding during the design process. However, a careful examination of Table 2-2, focusing of TC and VDD, particularly the three bottom-most rows, leads to the following observations:

- While TC successfully delivers the maximum possible value to the customer, it tends to pay less attention to the technical performance and the compatibility of the sub-components of the delivered product whether it is a building or any other industrial product (Bertoni et al. 2015).
- VDD, on the other hand, although it considers the value as an external boundary for the design problem, it prioritizes the engineering performance of the product over the value.

Bertoni et al. (2015) emphasize, in reference to the above observations, that the focus of the value-adding method shifts between customers and system performance, and thereby suggest creating a middle-ground focus that incorporates the impact of design decisions on both systems performance and value.

Additionally, it can be noted in Table 2-1 that both methods, i.e., TC and VDD, have a singular concept of value, which indicates that they evaluate the design against a single value, which is, in most cases, cost. However, sustainable construction requires the evaluation of the impact of design on several values concurrently, which implies the need for a tool that can assist the designers and stakeholders in performing such a task.

Based on the discussion previously presented, any developed value-adding framework must incorporate the following ten principles:

1) *Support concurrent design.* Concurrent design, also known as concurrent engineering and simultaneous engineering (Jo et al. 1993), is a "systematic approach to integrate product development that emphasizes the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle" (European Space Agency 2012). According to this definition, for a framework to support concurrent design it should (1) be structured in a systematic manner; (2) support team collaboration, which implies localizing the global targets to be handled locally by the teams from differing disciplines; and (3) employ simultaneous task performance, where several tasks can be carried out in parallel to reduce design time and ensure continuous improvement. Jo et al. (1993) add that the process should account for cost and life-cycle evaluation, as these also constitute principles of concurrent design.
2) *Allow for simultaneous improvement.* Simultaneous improvement, where several developments are achieved toward fulfilling several goals concurrently, is inherited in

the practice of concurrent engineering. An example of this in the construction industry is the process of designing the structural and mechanical systems, where two teams are working concurrently with the aim of improving the designs of the systems they are working on.

3) *Maintain efficient communication within and outside of the design team.* This is also inherited in the practice of concurrent design.
4) *Allow for cross-functional teams design*. The framework developed for adding value to the design should accommodate the collaboration of personnel from various backgrounds and disciplines.
5) *Focus on the design*. As the influence of decisions made during the design phase have the maximum influence on the performance of the various building systems during the lifecycle of the building (PMI 2013), the focus of the developed framework should be on the design phase. This requires the framework to be simple enough to be utilized throughout all design sub-phases, which implies that it can adapt according to the amount of information and can be repeated as many times as the decision maker desires.
6) *Account for the impact of value throughout the entire lifecycle of the project.* For instance, if design is to be evaluated against cost, both the cost of construction and the cost of operations should be considered.
7) *Incorporate all involved parties*. The framework should be flexible and inclusive in order to facilitate the participation of all stakeholders in the evaluation process of the design.
8) *The functional representation of values.* This requires presenting the value(s) in terms of a mathematical function that allows for the objective assessment of design decisions.
9) *Achieve a balanced focus on customers' needs and systems' performance*. A one-sided

focus represents one of the major drawbacks in the existing value-adding methods (see Bertoni et al. (2015) for more information). To create this balance, the present research proposes to (1) assess the interaction among the various values-systems components, and (2) assess the components-components interaction.

10) *Allow for multi-criteria lifecycle assessment*. Another improvement being sought through the research presented in this thesis is to extend the concept of value beyond the singularity that is prevalent in practice. This improvement will provide greater satisfaction for the stakeholders and will also support the construction industry endeavors to become a more sustainable industry, which is achieved through accounting equally for the economic, environmental, and social impacts of its products (i.e., buildings). The present research proposes to achieve this by means of multiple functions, where each corresponds to one of the desired values, and strives to collectively optimize their outcomes.

2.1.2 Value Visualization in the Construction Industry

2.1.2.1. Introduction

As previously mentioned, accounting for the potential receivable value for the end user during the early phases of the product development is complex, and therefore, several methods have been developed to assist designers in maximizing the value in their design outcomes as can be observed in Section 2.1. Nevertheless, the decisions made during the design phase have the greatest influence on the success of any value-adding process (Isaksson et al. 2009); Bertoni et al. (2013) consider that the quality of made design decisions is proportional to the effectiveness of the communication of values among stakeholders. To properly communicate values perceptions among stakeholders, Rischmoller et al. (2006) consider that visualization is vital to ensure value generation while the project is still in the design phase. Bertoni et al. (2013) further consider that the lack of tools able to visually demonstrate the interactions between design solutions and desired values hinders the efficiency of suggested designs. Therefore, creating a visual link between the desired values and the components of the product under design streamlines the design processes toward more value-oriented design decisions, and thus maximizes the added value (Collopy 2012). Thus, visual-aid tools that are capable of conveying values among the stakeholders during the design phase are indispensable to the success of value adding endeavors.

2.1.2.2. Value Visualization

In 1971, British singer, Rod Stewart, released his third album, *Every picture tells a story*. As poetic as this title may be, it projects a profound consensus on the ability of visual material to properly communicate ideas, concepts, and beliefs—and values. This phrase emphasizes the success of early applications of visualization, which can be traced back to 200 BC, in ancient

Egyptian survey maps, and the 2-dimentional projection of the spherical earth (Friendly 2008). The nineteenth century, however, marked the formation of modern graphics (Friendly 2008). A famous example of information visualizations of that era are Nightingale's rose diagrams (Brasseur 2005) and a map depicting Napoleon's march on Moscow (Peuquet and Kraak 2002; Kosara and Mackinlay 2013). Data and information visualization continued to develop, to undergo a major reformation between 1950 and 1975, before the advent of high dimensionality and dynamic data visualization which began in 1975 (Friendly 2008). A major milestone in this time frame, i.e., 1975 to present, occurred in 1987, which marks the beginning of computer generated information visualization (Van Wijk 2005). Information visualization is "the ability to take data—to be able to understand it, to process it, to extract value from it, to visualize it, and to communicate it" (Chen 2017). Therefore, information visualization is meant to assist in extracting value from raw data and transmitting it to the concerned audience. This perspective is supported by Fekete et al. (2008), who argue that the aim of information visualization is to extract insights from the set of data rather than explain the correlations in the data. In other words, visualization of information/data is the method of organizing information/data to support further computational processes (Simon and Larkin 1987).

Through the literature, it can be understood that researchers have provided comprehensive explanations for the function and definition of data/information visualization. However, to clarify how value visualization differs from that which has been presented, data and information must be understood as different steps toward building knowledge (Ackoff 1989), as indicated in Figure 2-1.

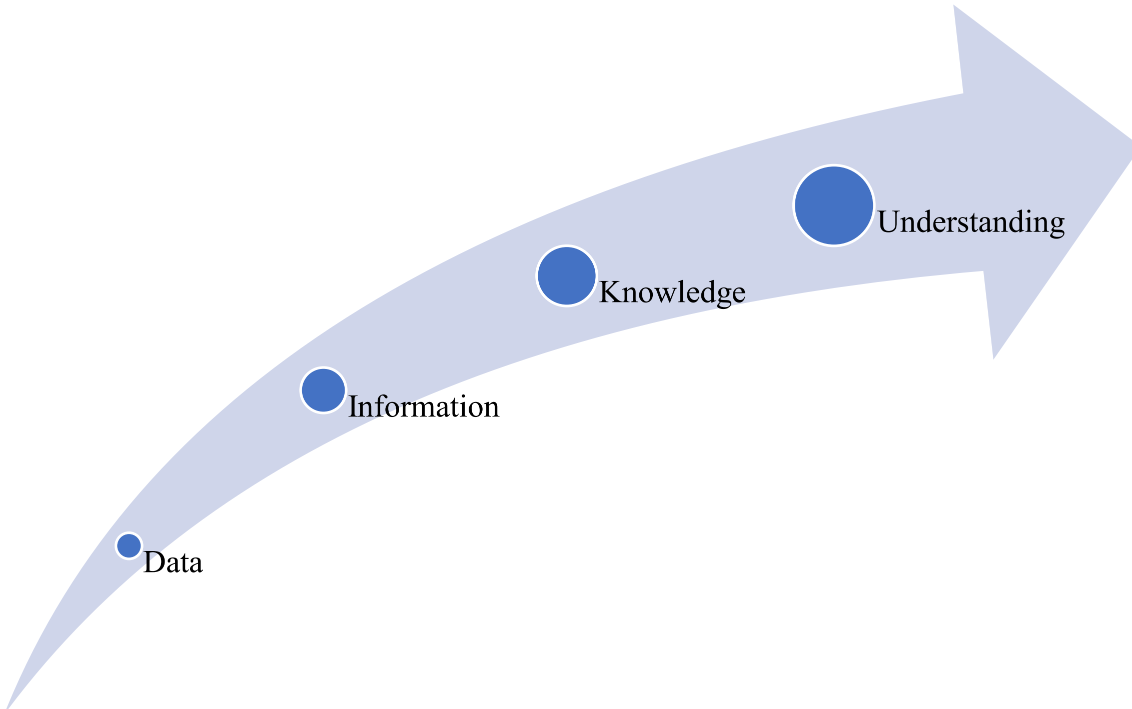


Figure 2-1 Evolution of data to value

Understanding, which is the ultimate product of data processing, leads to wisdom that is concerned with the judgment, evaluation, analysis, and growth of value (Ackoff 1989). Therefore, it is safe to argue that people are primarily familiar with data and information visualization (such as pie charts and info-graphs), but not value visualization (such as performance visualization). In this context, Karlsson and Norrman (2010) consider that value visualization is "concerned with the way that firms communicate and demonstrate the value of their Product-Service Systems (PSS), both internally and externally". Bu Hamdan et al. (2017) argue that what makes value visualization different from other types of visualization is its ability to visualize the impact of design decisions on the considered values. For instance, value visualization should depict how changing the size of a column will affect the cost of that column. Value visualization is thus defined as the process of displaying the influence of the interrelations between various components of the design outcomes on the value(s) under consideration, which works toward maximizing the value output of a given design by enabling understanding of the impact of design decisions on value outcomes throughout the lifecycle of the product. The work of Bertoni et al. (2013) and Bertoni et al. (2014) are outstanding representations of the previously presented definition which links the cost with the design outcomes in a 3D environment in order to support design efforts in the aeronautics industry.

2.1.2.3. Value Visualization in the Construction Industry

Based on the definition of value visualization and the characteristics of this process, the remainder of this section explores the applications of value visualization in the construction industry. According to Schroeder (2016), values can be listed under two categories: (1) intrinsic values, which are desired because of the goodness they represent; and (2) instrumental values, which are desired because they lead to something good. In this context, performance, with its various definitions and interpretations, is an intrinsic value, while stakeholder values (apart from performance), such as cost, amount of consumed energy, and carbon footprint of a building, can be considered as instrumental values. In addition to the previous classification of values, given that the construction industry is increasingly required to comply with sustainability measures, it is reasonable to use the sustainable aspects as the problem boundary for defining the values which are to be considered. In fact, sustainability encompasses three primary aspects: economy, society, and environment (Gibson 2006; Hansmann et al. 2012), which must be collectively fulfilled in order for a product to be considered sustainable. On that note, Mudge (1971) argues that a value must be quantifiable for it to be incorporated into a function and assessed. Therefore, in the search for related work pertaining to value visualization in the construction industry, efforts ought to focus on performance, economic values, and environmental values.

The performance of a product, a service, or a process is a result of the behaviour of its assemblies. In buildings, the performance is a result of the behaviours of building systems and their components, which are forecasted during the design stage; visualizing the performance, in this context, is a common practice in the construction industry, where several disciplines benefit from visualization features. In structural engineering, for example, it is common to visualize the behaviour of the selected structural system when affected by the design load (Ferri et al. 2006; Abell and Napier 2014; Gaweda 2015). An example can also be observed in building envelope design, such as visualizing the thermal interaction of the building with forecasted weather and the building assemblies (Korkmaz et al. 2010; Popova 2015). The advent of building information modelling (BIM) facilitated significant development for visualization by introducing parametric 3D models bound by constraints from several areas, including architectural, structural, and mechanical. However, it is useful to point out that performance visualization tackles the technical details of a single system, but not the interactions between various systems, and therefore performance visualization cannot be used for global (i.e., cross-disciplinary) decision making.

The economic aspect (i.e., cost), on the other hand, is a common measure for project success and is usually visualized in many forms, e.g., tabular and graphical. To provide a better understanding in this area, several methods have been developed to support a better display of cost data such as cash flow. However, among the considerable developments in visualization, BIM has offered the construction industry the ability to connect cost data to building elements, thus incorporating cost as an additional dimension that has gained attention from researchers (Barkokebas 2017). That being said, it should be noted that the visualization of cost in practice can be considered information visualization, but not value visualization, as it often fails to illustrate the interchangeable impacts between cost and building components.

Due to the increase of environmental awareness, the construction industry is required to perform operations that comply with environmental policies and to adopt a proactive approach toward its sustainable development (Nawi et al. 2014). Therefore, several researchers have developed tools to visualize environmental aspects such as the visualization of embodied carbon (Heydarian and Golparvar-Fard 2011; Memarzadeh and Golparvar-Fard 2012). Thus, the applications used to visualize environmental values do not support the display of more than one value.

In summary, two observations can be made based on the literature on visualization value in the construction industry: (1) the singularity of visualized value, and (2) little research has been conducted to address the influence of building elements on multiple values collectively for visualization during the design phase.

Therefore, the research presented in this thesis proposes a visualization framework that complies with the previously presented definition of value visualization and bridges the gap in the practice of value visualization in the two respects identified above: (1) the number of visualized values, and (2) visualization concurrent with design development.

2.2. Background: Tools and Concepts

2.2.1 Reliability Theory

"When you can measure what you are talking about, and express it in numbers, you know something about it…"[3] (Campbell 1863) In other words, measuring and expressing in numbers encompass the nature of reliability theory. The beginning of the 1930s marked the theoretical foundations of utilizing statistical information to predict the potential quality of manufactured

[3] William Thomson, 1st Baron Kelvin

products (Rausand and Arnljot 2004). As the industrial products produced after WWII became more complex and the predictability of the resultant quality became more difficult despite the use of high-quality components, the United States Navy's Bureau of Ships (BuShips) hired Aeronautical Radio, Inc. to assess the reliability of the electron tube, which is considered among the early applications of reliability theory in the 1930s (Knight 1991). Driven by the significant monetary investment of the United States in the Department of Defense and the National Aeronautics and Space Administration (NASA), reliability theory received considerable attention in the 1950s and 1960s, and in the 1970s the application of reliability expanded into the safety of constructing and operating nuclear power plants in the United Stated and abroad (Rausand and Arnljot 2004). The 1980s contributed to the application of reliability theory in research related to quality in the various spheres of the commercial marketplace such as electronic channel selection in radio and television and the digital clock (Knight 1991).

Currently, reliability theory is widely used in the design and maintainability of products in several industries, including aerospace, software, oil and gas, and many others (Blischke and Murthy 2003). However, there have been attempts to utilize reliability theory in the construction industry to increase the quality of deliverables. Turskis et al. (2012) present a comprehensive review of the "evolution" of the concept of reliability and its application in the construction industry regarding the risks and contingencies of time and cost. They conclude that the standardization of construction activity planning increases the quality and reliability of these activities. Researchers continue to scrutinize the similarity between the product and the project as systems in order to apply the concept of reliability to improve the performance of the construction project. For instance, the work of Tao and Tam (2012) treats the construction project as the system, and, as a result, they utilize reliability theory to maximize the optimality of the system's reliability. In other research, they utilize reliability theory to develop a multi-objective optimization model to decrease the construction cost (Tao and Tam 2013). A similar approach to construction projects can be found in the work of Kaplinski (2010), where reliability theory is deployed to improve the schedule performance of the project. Nevertheless, the use of reliability theory is not limited to the construction aspect of project performance enhancement. Researchers utilize reliability theory to study and improve the performance of structures, as can be seen in the work of Moses and Stahl (1979) who use this method to increase the reliability of offshore structures. This has led to the creation of structural reliability theory that is concerned with improving the quality of structural systems in a building using reliability theory (Thoft-Christensen and Murotsu 2012).

As can be seen, reliability theory has been widely implemented in several industries to increase the quality of a certain system and/or product, by means of utilizing statistical data to predict the future performance of that system and/or product. As the present research aims to incorporate the interdependencies among the building systems' components to understand how design decisions affect the performance of these components, reliability theory is the tool selected to analyze and understand this performance.

2.2.2 Quality Function Deployment (QFD)

The late 1960s witnessed several attempts to incorporate quality, as a desired value, into the design phase, such as the development of the processing assurance chart in the Bridgestone Tire plant in Kurume, Japan (Chan and Wu 2002). Another example is the functional deployment organization developed and applied by Ishihara in the late 1960s (Chan and Wu 2002). These attempts laid the foundation for the development of the Quality Deployment—or Quality Function Deployment (QFD)—method, which was formally introduced in 1972 in a paper titled, "Hinshitsu Tenkai" (quality deployment), written by Yoji Akao (Chan and Wu 2002). In 1983 the method was introduced to the American industry through the American Society for Quality Control. The approach continued to evolve, and in 2016, the first International Organization for Standardization (ISO) standard for QFD (ISO 16355) was approved (Mazur 2016). QFD is defined as a “planning methodology for translating customer needs into appropriate product features” (Khoo and Ho 1996), and it is widely implemented in the manufacturing industry around the world (Akao and Mazur 2003). Yet, this concept has yet to be fully utilized in the construction industry (Delgado-Hernandez et al. 2007), with the exception of some isolated practices as indicated by Khoo and Ho (1996), Yang et al. (2003), and Delgado-Hernandez et al. (2007).

In order to respond to customer requirements, QDF practitioners base their practice on four key concepts that are transformed into four documents to be used during the application process (Kathawala and Motwani 1994). These concepts include:

- Interpret the requirements of customers gathered through surveys into control features. The resulting document will be called, “Overall customer requirement planning matrix” (Li et al. 2014).
- Translate the overall customer requirement planning matrix into technical properties of the components. The resulting document will be called, “Final product characteristic development” (Kathawala and Motwani 1994).
- Define the parameters of the process and controls for the defined parameters. The resulting document will be called, “Process plan and quality control charts” (Dror 2016).
- Define the operation plan at the plant that guarantees to meet the previously defined performance parameters. The resulting document will be called, “Operating instructions”

(Kammerl et al. 2017).

The present research discusses the QFD because this method has managed to create a transition between the qualitative customer requirements and the technical aspect of the product (Akao and Mazur 2003), and therefore, it can be used to link the requirements of the MCLCA framework presented in 2.1.1.8 and the properties of design-related value-adding frameworks to ensure that the proposed framework bridges the gap that exists in the current practice of value-adding in the construction industry.

2.2.2.1. Using QFD to develop the attributes of MCLCA framework

The principles presented in Section 2.1.1.8 define the determinant characteristics necessary for the value-adding framework to improve value-oriented design in the construction industry. Quality Function Deployment (QFD), in this context, is a well-established method in the manufacturing industry that maps the customer requirements of a product with its technical features in order to achieve (1) higher quality compared to competitors, and (2) greater customer satisfaction. For this purpose, QFD is utilized to develop the framework that capitalizes on the commonalities amongst the existing value-adding method and helps to overcome their shortcomings. In the present research, the QFD of a product is used to develop a framework that has principles common to the customer requirements.

QFD uses the House of Quality (HoQ) as a visual method to demonstrate the relationships between the technical features of the product and customer requirements, and prioritize the design process by defining the attributes driving customer satisfaction (Hauser and Clausing 1988). The generic shape of HoQ is represented in Figure 2-2.

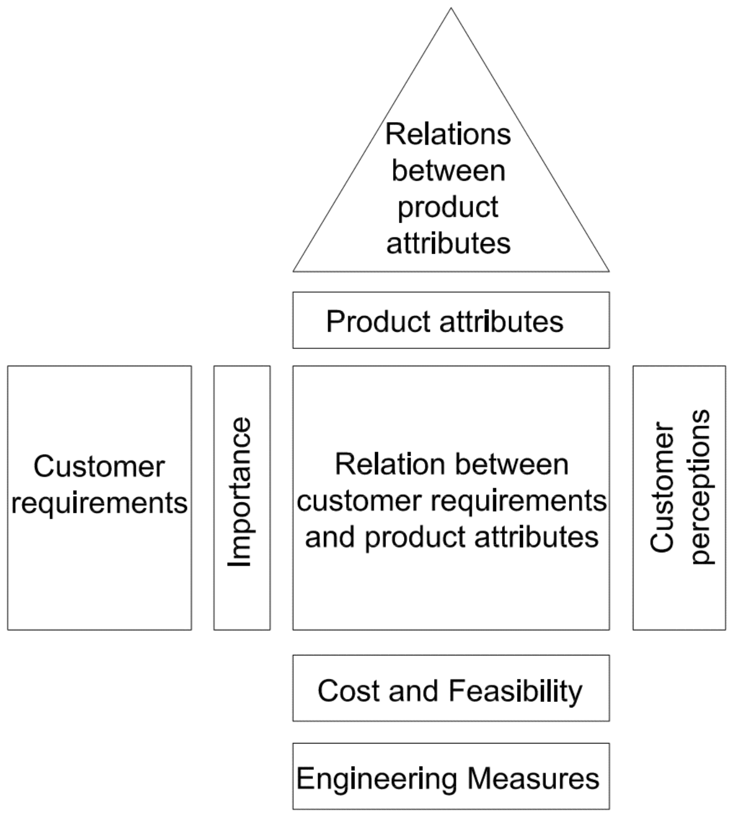


Figure 2-2 Generic shape of House of Quality (HoQ)

Building the HoQ begins with defining design requirements, followed by the product technical attributes, and finally mapping the technical attributes of the product with customer requirements, which allows the design team to determine the driving attributes to focus on during the design process. In the following section, this process will be explained in detail.

2.2.2.1.1. Definition of the framework requirements

The requirements to be fulfilled by the framework presented in this thesis are a combination of the common principles and the drawbacks to be overcome in the application of existing value-adding frameworks. These requirements, defined in Section 2.1.1.8, include:

1) support concurrent design (r_{c1}), which is broken down into the following secondary requirements: incorporate lifecycle assessment, perform tasks simultaneously, existence of systematic structure, team collaboration, and localize functions per team;
2) allow for simultaneous improvement (r_{c2});
3) maintain efficient communication within and outside of the design team (r_{c3});
4) allow for cross-functional teams design (r_{c4});
5) prioritize design phase (r_{c5});
6) account for the impact of value throughout the entire lifecycle of the project (r_{c6});
7) incorporate all involved parties (r_{c7});
8) assess the values using mathematical functions (r_{c8});
9) achieve a balanced focus on customer needs and performance of systems (r_{c9}), which is broken down into the following secondary requirements: assess the interaction of the value-system components and assess the component-component interaction; and,
10) allow for multiple value assessment (r_{c10}).

However, Wang and Ma (2007) argue that following a systematic approach to rank the requirements maximizes the potential of QFD implementation. The steps they propose to filter the requirements are as follows:

1. Analyze the overlap amongst the customer requirements.
2. Analyze the correlation and calculate the correlation index of the requirements.
3. Analyze the degree of importance to select the final list of customer requirements.

This pre-evaluation process helps to eliminate the waste inherent in considering requirements with marginal influence, or those that can be satisfied by satisfying other requirements. This process also increases the efficiency of the implementation process and the likelihood of meeting its objectives, and therefore, it is followed in the present research.

1. *Analysis of overlap amongst customer requirements*

For this analysis, requirements are assessed in pairs to determine the overlap between each pair. In this context, Wang and Ma (2007) distinguish between three types of overlap. (1) Inclusive overlapping occurs when a requirement, r_{ci}, is a component of another requirement, r_{cj}. In this case, r_{ci} is to be ignored. (2) Partial inclusiveness overlapping occurs when two requirements share common content. In this case, r_{ci} is partially included in r_{cj}; r_{ci} is then removed and a new requirement, r_{ci}', is created to encompass the components of r_{ci} that are not included in r_{cj}. (3) Independent requirements are a type of overlapping where there is no common content in the studied pair. This overlap results in keeping both requirements. Following this logic, Table 2-3 presents the pair comparison for overlapping.

Table 2-3 The analysis of the overlapping of requirements

Pair	Overlapping Type	Decision
(r_{c1}, r_{c2})	Inclusive, where r_{c2} is a sub-set of r_{c1}	Eliminate r_{c2}
(r_{c1}, r_{c3})	Inclusive, where r_{c3} is a sub-set of r_{c1}	Eliminate r_{c3}
(r_{c1}, r_{c4})	Partial inclusiveness, where part of r_{c4} is a sub-set of r_{c1}	Eliminate r_{c4} Create $r_{c4'}$ that includes “flexibility to accept feedback” $r_{c4'}$ and r_{c1} are independent
(r_{c1}, r_{c5})	Independent	No Change
(r_{c1}, r_{c6})	Inclusive, where r_{c6} is a sub-set of r_{c1}	Eliminate r_{c6}
(r_{c1}, r_{c7})	Inclusive, where r_{c2} is a sub-set of r_{c7}	Eliminate r_{c7}
(r_{c1}, r_{c8})	Independent	No Change
(r_{c1}, r_{c9})	Independent	No Change
(r_{c1}, r_{c10})	Independent	No Change
(r_{c4}', r_{c5})	Independent	No Change
(r_{c4}', r_{c7})	Independent	No Change
(r_{c4}', r_{c10})	Independent	No Change
(r_{c5}, r_{c9})	Independent	No Change
(r_{c5}, r_{c10})	Independent	No Change
(r_{c9}, r_{c10})	Independent	No Change

Based on the decisions presented in Table 2-3, the new set of requirements is as follows:

- support concurrent design (r_{c1});
- flexibility to accept feedback (r_{c2});
- focus on design (r_{c3});
- assess the values using mathematical functions (r_{c4});
- achieve a balanced focus on customers' needs and systems' performance (r_{c5}); and,
- allow for multiple value assessment (r_{c6}).

2. Analysis of correlation and calculate correlation index of requirements

This step further investigates the interactions amongst the set of requirements, where it is possible to define the following types of correlations, as per Wang and Ma (2007), between a pair of requirements (r_{ci}, r_{cj}):

- opposite, when (r_{ci}, r_{cj}) cannot be satisfied at the same time;
- non-correlated, when there is no interaction among the studied pair of requirements;
- conflicted, when increasing the satisfaction of r_{ci} leads to decreasing the satisfaction of the r_{cj}, and vice versa;
- collaborated, when increasing the satisfaction of r_{ci} increases the satisfaction of r_{cj}, and vice versa;

The results of this pair-comparison are presented in the correlation matrix *C*, which has the following structure:

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1i} \\ c_{21} & c_{22} & \cdots & c_{2i} \\ \vdots & \vdots & \ddots & \vdots \\ c_{i1} & c_{i2} & \cdots & c_{ii} \end{bmatrix}$$

where c_{ij} is the correlation factor between requirement i and requirement j. As per Wang and Ma (2007), c_{ij} is assigned the following values: 1, 3, 7 to represent weak, medium, and strong correlation; $-1, -3, -7$ to represent weak, medium, and strong conflict; 0 if there is no correlation; and finally 9 for c_{ii}. Note that $c_{ij} = c_{ji}$.

After the correlation matrix is formed, the correlation index for each requirement is calculated using Equation 2-4.

$$R_i = \frac{1}{c_{ii}} \sum_{\substack{j=1 \\ j \neq i}}^{I} c_{ij} \tag{2-4}$$

For the shortened list of requirements, the correlation matrix will be as follows:

$$C = \begin{bmatrix} 9 & 7 & 1 & 3 & 3 & 1 \\ 7 & 9 & 0 & 3 & 1 & 3 \\ 1 & 0 & 9 & 1 & 1 & 1 \\ 3 & 3 & 7 & 9 & 3 & 3 \\ 3 & 1 & 1 & 3 & 9 & 7 \\ 1 & 3 & 1 & 3 & 7 & 9 \end{bmatrix}$$

The correlation index for each of the requirement is presented in Table 2-4.

Table 2-4 Requirements correlation indices

Requirement (r_{ci})	r_{c1}	r_{c2}	r_{c3}	r_{c4}	r_{c5}	r_{c6}
Correlation Index (R_i)	1.67	1.56	0.44	2.11	1.67	1.67

3. *Analysis of degree of importance to select final list of customer requirements*

The final elimination of non-value-adding requirements is performed through the correlation index, where Wang and Ma (2007) suggest:

$$if\ 0 < K_i \leq 1 \ \rightarrow the\ requirement\ is\ satisfied\ by\ satisfying\ other\ requirements$$

$$if K_i \leq -1 \rightarrow the\ requirement\ is\ severly\ conflicting\ other\ requirements$$

For both scenarios, the corresponding requirement is to be eliminated from the requirements list. Then, for the remaining requirements, the importance degree is proportional to the value of the correlation index, thereby the greater the correlation, the greater the importance degree. Based on the values presented in Table 3-3, r_{c3} should be excluded as it has a correlation index that is smaller than 1. The importance degree based on the correlation indices are presented in Table 2-5.

Table 2-5 Importance degree of requirements

Requirement (r_{ci})	r_{c1}	r_{c2}	r_{c3}	r_{c4}	r_{c5}	r_{c6}
Importance Degree	3	1	Excluded	5	3	3

The set of primary requirements, their importance, and their breakdown are presented in Table 2-6.

Table 2-6 Final list of requirements

Primary Requirement	**Importance Degree**	**Breakdown**
Functional representation of values	5	-
Support concurrent design	3	Incorporate Lifecycle Assessment
		Perform Tasks Simultaneously
		Existence of Systematic Structure
		Team Collaboration
		Localize Functions Per Team
Achieve a balanced focus on customers' needs and systems' performance	3	Assess the Value-System Components Interaction
		Assess the Component-Component Interaction
Allow for multiple value assessment	3	-
Flexibility to accept feedback	1	-

As the framework requirements are defined, the next step is to define the attributes the framework should possess.

2.2.2.1.2. Definition of the framework attributes

Amongst the five methods previously discussed in the literature review, TC/TVD and VDD are the methods that have been chiefly developed to support design effort. Hence, they constitute a solid case study to define the potential attributes that should characterize the framework the present research aims to develop.

Beginning with VDD, notably, this method is the iterative in nature, in that the design cycle undergoes a series of identical steps multiple times until the constraints are satisfied. VDD also has a fixed structure, which involves a pre-defined set of steps in a certain order to be followed by the design team. A major step in the VDD process is to build the value model, where the components of systems are linked with the value (in most of the corresponding literature, the value is cost). This function is used to evaluate the compliance of design systems with the value set by stakeholders. Furthermore, as VDD claims to prioritize the technical performance of the design system, it emphasizes the incorporation of the interactions among design components and suggests defining a function that is derived from the value model to bound the design of the components. Table 2-7 summarizes the attributes and some relevant literature where more details can be found.

Table 2-7 Value-driven Design attributes

VDD Attributes	Relevant Literature
Iterative process	(Castagne et al. 2006; Isaksson et al. 2009; P. D. Collopy and Hollingsworth 2011; Cheung et al. 2012).
Functional assessment of the value	
Incorporate interactions among components	
Define component object function	

Ballard and Pennanen (2013) present a framework for the application of TC/TVD in the construction industry, where the following characteristics prevail: (1) iterative nature, (2) sequential nature, (3) there is a function for value satisfaction assessment, and finally (4) there are several steps in the decision-making process before the final decision is made. This discussion, in addition to the information presented in Table 2-7, leads to the following commonalities between the two design frameworks:

- the interactive nature of the framework;
- the sequential structure, where there are certain steps to follow in a given order; and
- the value is represented as a function.

These three points are the key attributes of the framework. However, further investigation leads to the following observations:

- The functional assessment of the value entails incorporating all the influencing factors, causing difficulty for practitioners to find the solution and check the compliance of the design with the requirements in a timely manner. Therefore, it is better to localize the function into each system and/or component to allow the practitioners to deal with a smaller number of variables, which requires the continuity of the original function, making it possible to find the derivatives.
- One of the shortcomings sought to be overcome through the present research is to allow for multi-criteria assessment; therefore, the suitability of the function to accommodate multi-criteria assessment is essential.
- For the assessment to satisfy the requirement of "concurrent engineering", the value(s) must be evaluated throughout the lifecycle of the product. Therefore, the function must assess the lifecycle impact on a given value.

Based on the information that is presented in this section, the attributes to be selected for the framework include:

- having iterative nature;
- having a consistent sequential structure;
- assessing the value(s) through a function;
- the value function(s) should be of a continuous nature;
- supporting lifecycle assessment of value(s); and
- incorporating the technical performance of components in the evaluation process.

The next step is to map these attributes with the previously defined requirements.

2.2.2.1.3. Development of the House of Quality (HoQ)

The HoQ for the framework development is built to define the driving attributes for the fulfillment of the development process. This process is facilitated using templates from QFD Online, which can be acquired via http://www.qfdonline.com/templates/. Table 2-8 presents the customer requirements as define in Section 2.2.2.1.2 and their relative weight.

Table 2-8 The framework requirements and their relative weight

Row Number	Demand Quality (Customer Requirements)	Weight/ Importance	Relative Weight	Competitive Analysis (0=Worst, 5=Best)	
				TC	VDD
1	Functional representation of values	5	10.67	2	3
2	Incorporate Lifecycle Assessment	3	10.00	4	4
3	Perform Tasks Simultaneously	3	10.00	3	4
4	Existence of Systematic Structure	3	10.00	2	3
5	Team Collaboration	3	10.00	3	3
6	Localize Functions per Team	3	10.00	0	3
7	Assess the Values-System Components Interaction	3	10.00	2	3
8	Assess the Component-Component Interaction	3	10.00	0	4
9	Allow for multiple value assessment	3	10.00	1	1
10	Flexibility to accept feedback	1	3.33	4	4

Note that the relative weight is calculated based on the importance of the requirement. The relative weight (w_i) for the requirement (i) of an importance degree (I_i) is calculated as follows:

$$w_i = \frac{I_i}{\sum_{i=1}^{n} I_i} \tag{2-5}$$

Table 2-9 presents the relationship between the framework attributes and requirements.

Table 2-9 Relations between attributes and requirements

Relationship Between Requirements:
9 - Strong 3 - Moderate 1 - Weak

Row Number	Max Relationship Value in Row	Relative Weight		1	2	3	4	5	6
			Column Number	1	2	3	4	5	6
			Max Relationship Value in Column	9	9	9	9	9	9
			Requirement Weight	366.67	426.67	680	420	413.33	820
			Relative Weight	11.73	13.65	21.75	13.43	13.22	26.23
			Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	0	3	3	4	1	6
			Minimize (▼), Maximize (▲), or Target (x)	x	▲	▲	▲	x	▲
			Target or Limit Value						
			Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / **Demanded Quality (a.k.a. "Customer Requirements" or "Whats")**	Having Iterative nature	Having a rigor sequential structure	Assessing the value(s) through a function	The value function(s) should be of a continuous nature	Supporting life cycle assessment of value(s)	Incorporating the behaviour of components in the evaluation process to account for the technical performance
1	9	16.67	Functional representation of values	1	1	9	3	3	9
2	9	10.00	Incorporate Lifecycle Assessment	3	1	9	3	9	9
3	9	10.00	Perform Tasks Simultaneously	1	9	3	9	1	9
4	9	10.00	Existence of Systematic Structure	3	9	1	1	1	3
5	9	10.00	Team Collaboration	3	3	3	9	1	9
6	9	10.00	Localize Functions per team	3	9	9	9	3	9
7	9	10.00	Assess the Value-System Components Interaction	9	3	9	1	9	9
8	9	10.00	Assess the Component-Component Interaction	9	3	9	1	3	9
9	9	10.00	Allow for multiple value assessment	1	1	9	1	9	9
10	9	3.33	Flexibility to accept feedback	9	9	3	9	1	3

Based on the information presented in Table 2-8 and Table 2-9, the full HoQ for the framework is presented in Figure 2-3.

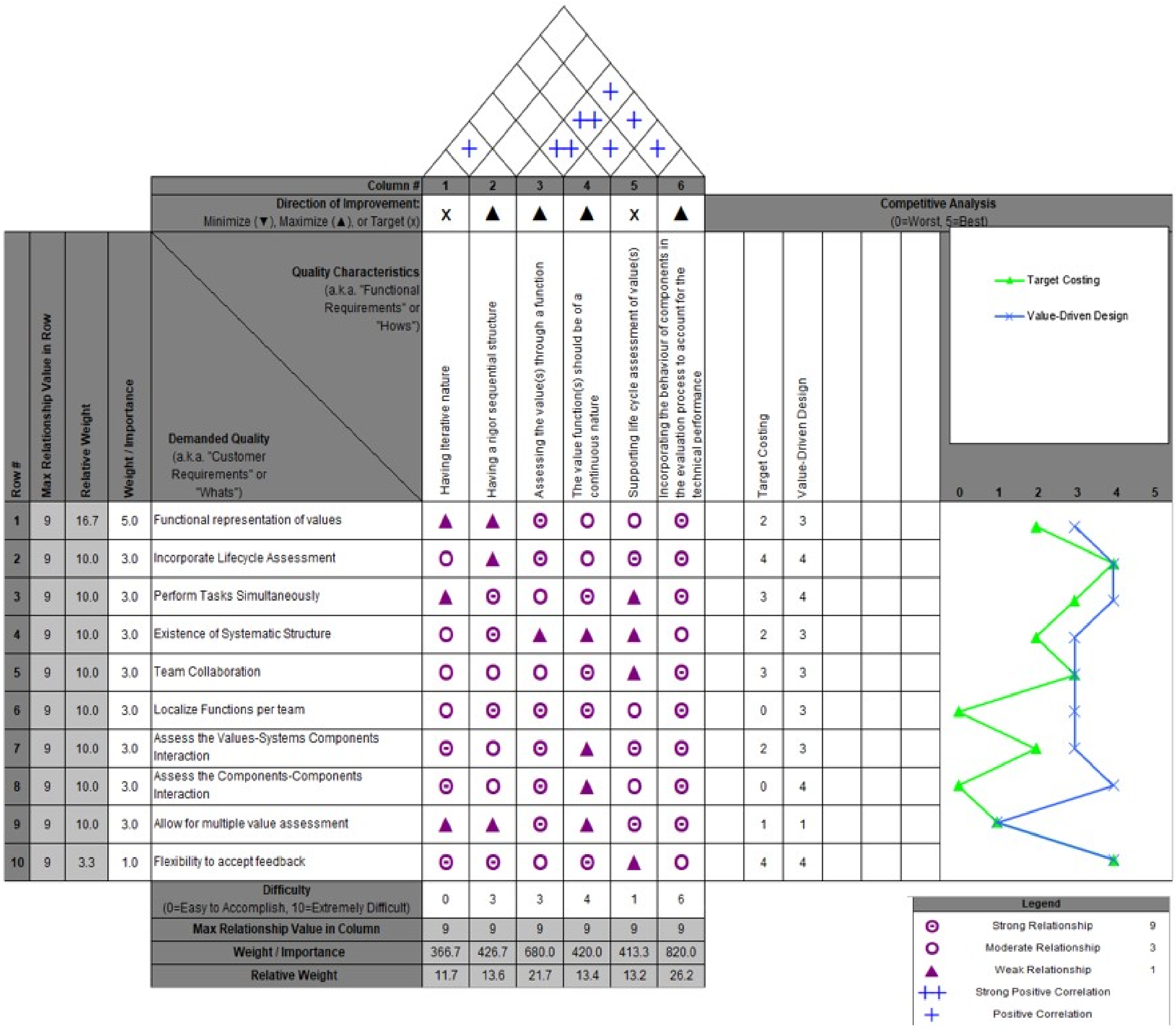


Figure 2-3 The HoQ for the framework

The summary of the QFD analysis is presented in Table 2-10.

Table 2-10 QFD analysis summary

Row Number	Quality Characteristics (Functional Requirements)	Requirement Weight	Relative Weight
1	Having iterative nature	366.67	11.73%
2	Having a consistent sequential structure	426.67	13.65%
3	Assessing the value(s) through a function	68.00	21.75%
4	The value function(s) should be of a continuous nature	420.00	13.43%
5	Supporting lifecycle assessment of value(s)	413.33	13.22%
6	Incorporating the technical performance of components	820.00	26.23%

As can be observed in Table 2-10, the most influential driver to fulfill the requirement of the development process is incorporating the behaviour of components, which makes it possible to account for the technical performance (Row 6 in Table 2-10) in the evaluation process. Modelling the problem in the shape of a mathematical function (Row 3 in Table 2-10) is the second most important driver, followed by having well-structured steps to follow (Row 2 in Table 2-10). The continuous nature of the functions used to describe the problem (Row 4 in Table 2-10) is the fourth step, followed by lifecycle assessment (Row 5 in Table 2-10) and finally the iterative nature (Row 1 in Table 2-10). Based on the minor relative importance of the iterative nature to the fulfillment of the requirements, the framework must be usable with and without iteration.

2.2.3 Utility Theory

Utility is a metric that measures the preference consumers have toward certain goods (Briggs 2014). This concept is rooted in the work carried out by Adam Smith in the 1700s, through which he distinguished between the value in use and the value in exchange, and notably indicates the effect of preference on the value (Stigler 1950a). Later in 1789, Jeremy Bentham added social and moral aspects to the concept of utility, proposing a measure of the quantity of pain and pleasure in his endeavour to create a rational system of criminal law (Stigler 1950a; Bobzin 2017). In the mid 1800s, utility theory underwent a significant improvement through the work of Jule Dupuit who clearly distinguished between diminishing marginal utility and total utility, which Gossen then built upon to introduce the fundamental principle of diminishing marginal utility (i.e., between utility and demand curve) (Stigler 1950a; Katzner 1970). As of the 1870s, utility theory began to receive considerable recognition from economists and mathematicians through the introduction of the indifference curves (Stigler 1950a; Bobzin 2017). The development of utility theory continued in the twentieth century, which witnessed improvement pertaining to utility maximization, demand function, defining the mathematical systems for choice theory, and the expected utility theory (Stigler 1950b; Katzner 1970; Quiggin 1982; Bobzin 2017).

Presently, utility theory is utilized in a wide range of decision-making applications across several disciplines (Edwards 2013). Researchers in the construction industry are also exploring the implementation of utility theory applications to support their decision-making endeavours. Benjamin of Stanford University proposes the use of utility theory to assess the best-fit bidder in construction contract bidding, where he uses an exponential and bilinear utility function to assess the alternatives (Benjamin 1969). Modelling risk and uncertainties in construction projects is among the highly common applications of utility theory in construction. For example, Mohamed and McCowan (2001) introduce a model to assess the monetary and non-monetary aspects of investment alternatives, where expected utility theory is used to assess the risk inherent in the evaluation process. In other work, Multi Attribute Utility Theory (MAUF) is deployed to develop a multi-objective decision-support system for use in resolving disputes related to cost and time in the construction industry (Jelodar et al. 2014). MAUF is also utilized to develop a model to assess the engineering performance during the design stage, thereby allowing the design team to increase the efficiency of the design effort (Georgy et al. 2005).

The application of utility theory is dependent on assessing the utility of each of the alternatives using a utility function (Blokhin 2015). Now, assuming a utility function $u: X \rightarrow \mathbb{R}$, and two alternatives, A and B, then A is preferred over B (or $A^P B$) only if $u(A)>u(B)$ (Serrano and Feldman 2011). Calculating the utility of an alternative can be performed in two manners (Fishburn 1968):

- without probabilities; and
- using expected utility theory.

When using the concept of utility without probabilities, only the utility of the alternatives is assessed using the utility function, as explained earlier. While, when using the expected utility theory, the resultant utility should be adjusted based on its likelihood of occurrence.

Notability, if an alternative, A, consists of several components, c_1, c_1… c_n, where $A = c_1 + c_1 + \ldots + c_n$, the utility of A, or ($u(A)$), can be expressed as follows (Juster 1990):

$$u(A) = \sum_{i=1}^{n} u(c_i) \tag{2-6}$$

$$u(A) = \sum_{i=1}^{n} u(c_i) \times P(c_i) \tag{2-7}$$

where, Equation 2-6 is applied when no probabilistic analysis is performed, and Equation 2-7 is applied as part of the expected utility practice. Note that $P(c_i)$ is the likelihood of c_i occurring.

Utility theory, as can be observed, is perceived as a highly reliable approach to objectively assess the various options within the given assessment criteria. As the present research proposes a framework to evaluate several design alternatives in order to choose that which is near optimal, utility theory is utilized to perform the final assessment. However, in the present research utility will be implemented without probability.

3. Methodology

3.1. Introduction

In order for the research presented in this thesis to achieve its goals, two frameworks are introduced: (1) a multi-criteria lifecycle assessment design framework that incorporates the technical performance of building systems, and (2) a value-visualization framework that assists designers and decision makers in rapidly assessing the impacts of design decisions on value. Figure 3-1 illustrates the flow of research toward the developed solutions, which begins the development of a framework that incorporates the findings of state-of-the-art research and practice to help stakeholders evaluate the existing design against the desired value. The next phase of this methodology is concerned with improving the stakeholders' visual experience in evaluating the considered assessment criteria through the development of a tool that visually depicts the interaction between the system components of a building and the assessment criteria in order for stakeholders to comprehend how their decisions are projected in terms of values.

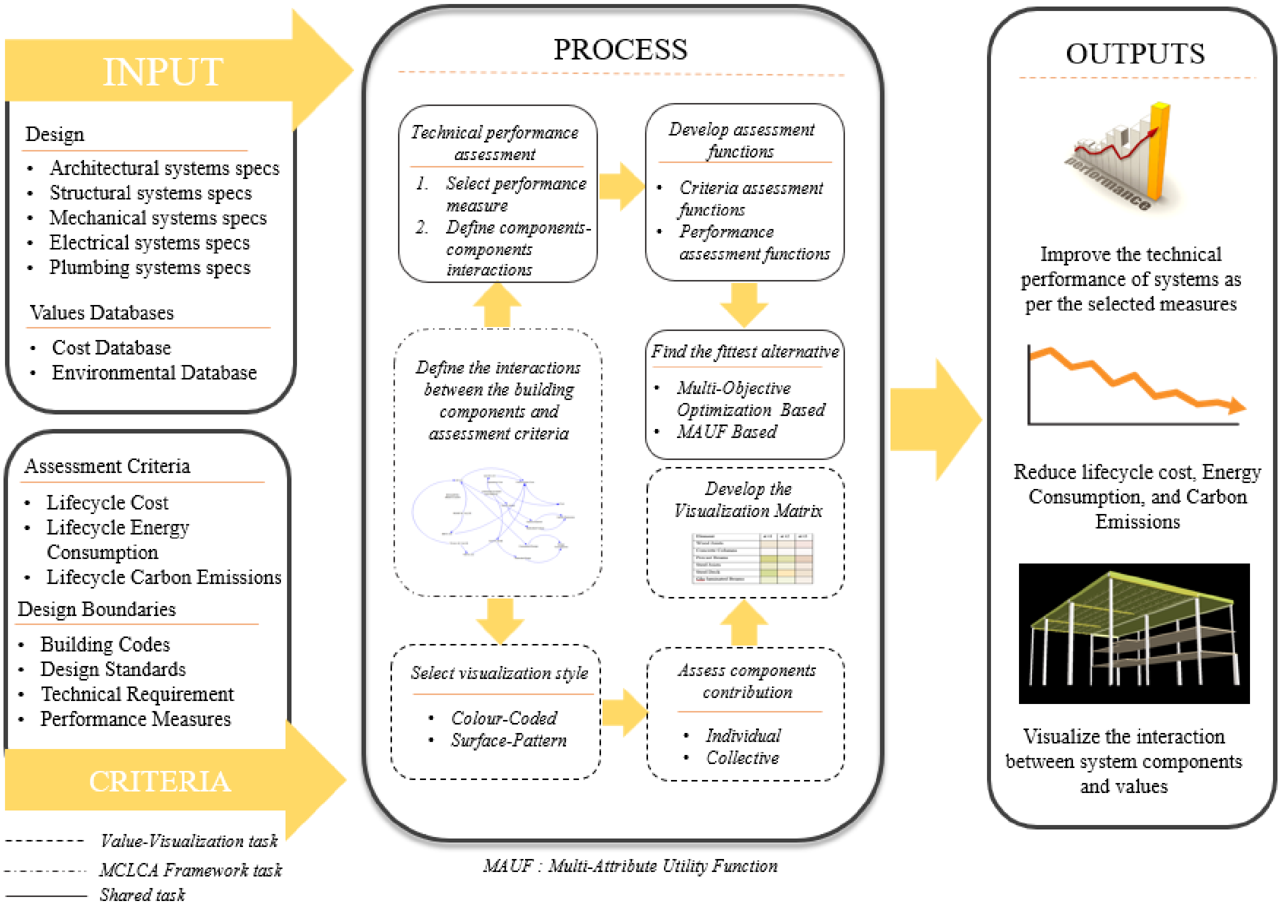


Figure 3-1 Methodological workflow

3.2. Phase 1: Developing an MCLCA design framework

3.2.1 Investigation of the MCLCA attributes

In this section, the attributes ranked in Table 2-10 that require further clarification are explored in order to draft the major flow in the framework.

3.3.4.1 Incorporation of component performance

Despite often being overlooked by designers, the influence of design decisions on a system may in turn inflict varying influence on the performance of other systems due to the interdependencies among the building systems. For instance, the level of illumination in each room is a function of natural and artificial illumination. The more natural light the room receives, the less artificial lighting it requires, and therefore, the less electricity demand required. However, the amount of natural illumination is dependent on the size of the opening(s) (such as a window) and the orientation of the building, both of which also affect the heat load that bounds the capacity of the heating system. On the other hand, more artificial lighting is indicative of more heat gain from lighting fixtures, and, therefore, more cooling load. Another example is an ice rink, where its structure is made of steel. The process of freezing and melting the rink increases the humidity in the space, which increases the rate the corrosion of the steel and jeopardizes the integrity of the structural system. The ventilation system is responsible for controlling the humidity levels in the conditioned space. Therefore, an underperforming ventilation system in this case increases the chances of structural failure, thereby decreasing the potential performance of the structural system.

Hence, it is important to quantitively evaluate the influence of selected design parameters on the behaviour of systems in the same discipline and of other disciplines. This evaluation is carried out through the analysis of the performance of individual components, which is linked by the interaction network to determine their influence on the systems. In this context, the reliability of the system is its ability to function as it is designed to function (Blischke and Murthy 2003). This definition of reliability aligns with the definition of performance as the ability to meet the pre-defined purpose (Nenadl 2016), which justifies the interchangeable use of reliability and performance. Therefore, the concept of reliability theory will be utilized by the framework to model the performance of building systems.

Using Reliability Theory to model systems performance

Reliability measures the manner by which an item performs a function (which is the service the system is designed to deliver) under environmental and operational conditions during a given period (ISO 8402 1999). Reliability analysis seeks to predict the behaviour of the studied item by studying a mathematical function that represents this item. The item can be a system (e.g., a car's engine), a component in a system (e.g., a car's tires), or a set of systems (e.g., a car). The analyst is free to formulate the mathematical function that is used for reliability analysis, through which they represent the system with one function, or a set of functions. One commonly used model in reliability analysis is the failure model, which can assist in predicting the time until the first failure of the system (time of failure *T)* when that system is under the operational conditions.

Note that *T* is not necessarily measured in units of time. It can also measure other concepts such as the amount of generated energy by an HVAC system, the number of kilometers a car drives, or the number of clicks made on a computer mouse.

In the failure model there are four measures for the reliability of a system:

- The reliability function (or survivor function) $R(t)$; $R(t) \geq 0$
- The failure rate function $z(t)$
- The mean time to failure (MTTF)
- The mean residual life (MRL)

In fact, the survivor function is the attribute of systems with a random nature that captures the probability of these systems to continue to function after a specific point in time. Therefore, in the failure model of reliability, the survivor function is used to mathematically model the randomness (stochasticity) of the studied systems. In this context, it is important to point out that the failure model does not account for the deviation from the designed performance, as the studied system/component is considered to function as designed until it ultimately fails.

For a sample of the time to failure of a system, the likelihood, *F(t)*, that a system will fail within a time interval (*0, t*) can be written as follows:

$$F(t) = \Pr(T \leq t) \tag{3-1}$$

Whereas, the probability density function is expressed as Equation 3-4:

$$f(t) = \frac{d}{dt}F(t) = \lim_{\Delta t \to 0} \frac{F(t + \Delta t) - F(t)}{\Delta t} = \lim_{\Delta t \to 0} \frac{\Pr(t \leq T \leq t + \Delta t)}{\Delta t} \tag{3-2}$$

When *Δt* is small, Equation 3-2 leads to

$$\Pr(t \leq T \leq t + \Delta t) \approx f(t).\Delta t \tag{3-3}$$

Based on Equations 3-1 and 3-3, it is possible to define the measures of reliability in the failure model as follows:

- The reliability function (or survivor function) *R(t)*:

As *R(t)* indicates that the studied system will not fail in a given interval *(0, t)*, then it can be defined as follows:

$$R(t) = 1 - F(t) = \Pr(T > t) \;\; for\; t > 0 \tag{3-4}$$

- The failure rate function *z(t)*:

z(t) is expressed as per Equation 3-5.

$$z(t) = \frac{f(t)}{R(t)} \tag{3-5}$$

- The mean time to failure (*MTTF*):

$$MTTF = \mathrm{E(T)} = \int_0^\infty t.f(t).dt \tag{3-6}$$

- The mean residual life (MRL):

$$MRL(t) = \mu(t) = \frac{1}{R(t)} \int_{0}^{\infty} R(x)dx \tag{3-7}$$

For additional information pertaining to the extraction of the given function, the reader can refer to System Reliability Theory Models and Statistical Methods (Rausand and Arnljot 2004).

For an example of how to use these functions, assume an item that has the following reliability function:

$$R(t) = \frac{1}{(0.1 + 2t)^4} \tag{3-8}$$

where *t* measures time in years.

The failure rate function will be expressed as follows:

$$z(t) = -\frac{d}{dt} \ln\big(R(t)\big) = \frac{8}{(0.1 + 2t)^5} \tag{3-9}$$

The mean time to failure (MTTF) will be expressed as follows:

$$MTTF = \int_0^\infty R(t).dt = \int_0^\infty \frac{1}{(0.1 + 2t)^4}.dt = 166.67\ years$$

Thus, it can be observed that the system is expected to perform as designed for 166.67 years before it fails and requires replacement.

And finally, the mean residual life (MRL) can be expressed as,

$$MRL(t) = \mu(t) = \frac{1}{R(t)} \int_{0}^{\infty} R(x)dx = 166.67 * (0.1 + 2t)^4$$

It should be noted that case study 2, which is outlined in Section 4.2, provides a detailed example of the mathematical process from raw data to the development of the survivor function.

The selection of the failure model allows decision makers and designers to evaluate the expected lifespan of the concerned system, where, in this context, the longer the duration of T, the better the performance of the system.

3.3.4.2 Functional assessment of design alternatives

The functional assessment of design alternatives involves forming a mathematical model that demonstrates the interrelations amongst the variables, constants, and targets. This mathematical model is called the value model, where the purpose of building such a model is to create objective bases through which design outcomes can be assessed. In this context, it is possible to differentiate between two types of value models: an investment-related model and a general model.

The investment-related value model is used to evaluate business opportunities such as constructing an office building. In this type of model, all values are substituted with one value (preferably cost), then any method of business strategic models can be used to populate the value model and assess the design accordingly.

The general-purpose model is used when the stakeholders are interested in the overall impact of the building on the values (such as the total cost and the overall effect on the environment) rather than the business opportunity it represents, such as hospitals, schools, or residential buildings built for the personal use of the owners, among others. For this type of value model, the problem is multi-objective optimization, such as minimizing cost and energy consumption.

3.3.4.3 Having a sequential structure

Following a sequential process while using a framework facilitates the application and enables tracking. Furthermore, it allows for future automation, and the sequential style results in a more efficient programming effort.

3.3.4.4 Continuous function

The need to localize the global attributes necessitates the continuity of the value model, thus it is possible to derive the global function according to the design components. The localized functions interpret the global requirements of the value model into the design process of each component. Given that not all global design attributes are related to a certain component (e.g., interior columns have a negligible effect on the heating load, and therefore, the operational energy and CO_2 emission), it is impractical to force the design to comply with all the requirements. Thus, reducing the dimensionality of the global values model provides greater flexibility for the application of the method. The local objective function measures the change a certain design attribute makes to the global objective function.

Assume the function $P = f(x)$, where the change x creates in relation to P can be expressed by Equation 3-10.

$$Ch_x = \frac{dP}{dx} \times x \tag{3-10}$$

Now consider $x = f(y)$, where the change y creates in relation to P can be expressed by Equation 3-11.

$$Ch_y = \frac{dP}{dx} \times \frac{dx}{dy} y \tag{3-11}$$

Then, assume a function, $GL = O\ (v_1, v_2, v_3, \ldots v_n)$, that represents the value model. Now, considering the attributes of the component i in the building system are $a_1, a_2, a_3, \ldots, a_n$, the local objective function for this component (GLi) can be written as,

$$GL_i = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{\partial f}{\partial v_j} \times \frac{\partial v_j}{\partial a_i} \times a_i \tag{3-12}$$

Finding the gradient analytically is a time-consuming process, thus it is possible to use sensitivity analysis to proximate the value of the gradient pertaining to a certain attribute. While s_{ij} represents the sensitivity of a value component (j) to the changes of a design attribute (i), Equation 3-12 can be written as follows:

$$GL_i = \sum_{i=1}^{n}\sum_{j=1}^{m} s_{ij} \times a_i \tag{3-13}$$

The attributes the framework should possess are well defined. The remaining work in this development process is to define the information and decision flow in the framework.

3.2.2 Definition of the framework

Based on the previous discussion, it is possible to propose a high-level diagram that represents the framework for value-adding that incorporates the findings in Section 3.2.1. Figure 3-2 depicts the high-level diagram of the framework.

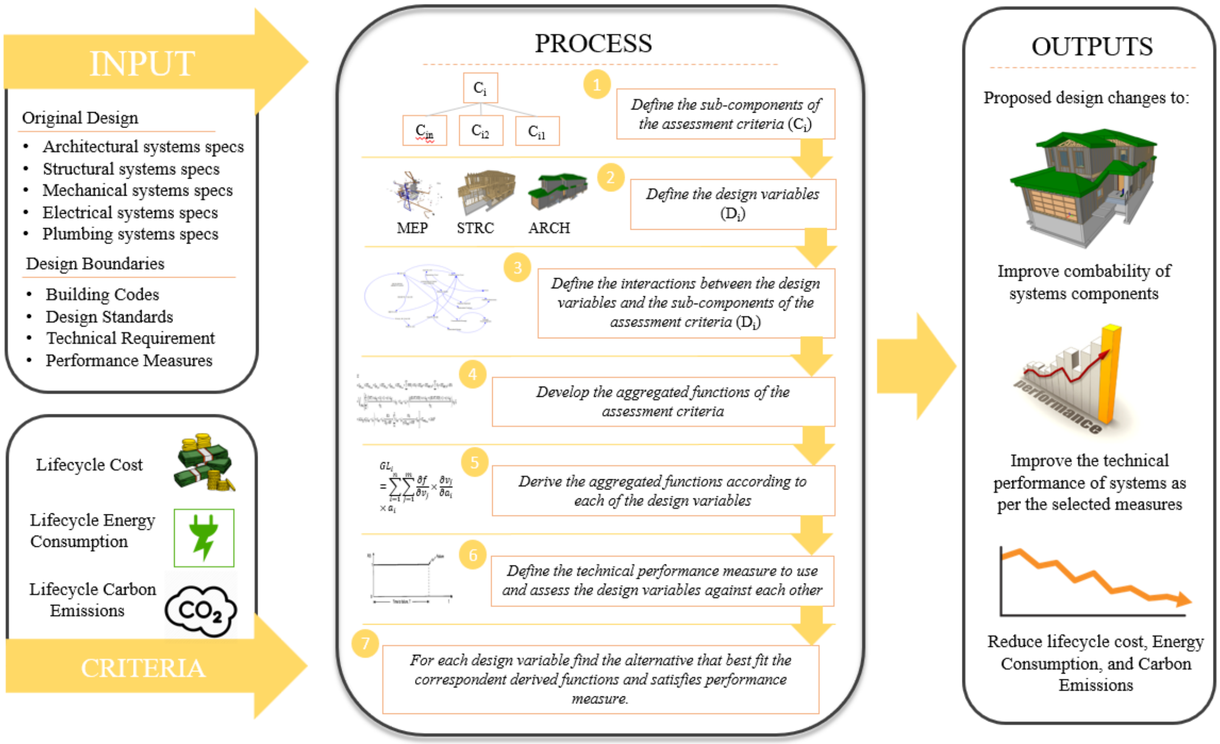


Figure 3-2 High-level description of proposed framework

The application of the proposed framework follows seven steps, as outlined below:

1. *Define the sub-components for each of the assessment criteria*

This step includes breaking down the assessment criteria (i.e., cost, energy consumption, and carbon emissions) and defining the relationships between each criterion and its correspondent sub-component. For example, construction cost (C_{1c}), operational cost (C_{1o}), and maintenance cost (C_{1m}) comprise the sub-components of lifecycle cost (C_1); where cost is the sum of these three components, or:

$$C_1 = \sum C_{1i}\,; i \in \{c, o, m\} \quad (3\text{-}14)$$

Breaking down the assessment criteria into phase-specific (e.g., construction and operation) components facilitates further processes in this framework; primarily the defining of the interaction between the design variables and the assessment criteria, as it makes declaring the relationships more intuitive.

2. *Define the design variables*

Design variables (D_k) are the attributes to be improved through the application of the proposed framework. There is no constraint on the number of variables, nor on the disciplines (i.e., architectural, structural, and MEP) to which they belong. For instance, the assessment team can choose the R-value of the wall, the construction material of the studs, the building orientation, etc.

3. *Define the interactions between the design variables and the sub-components of assessment criteria*

This step includes determining the underlying equations that govern the relations among sub-components of the assessment criteria and the design variables. For example, considering the criterion sub-component is the construction cost (C_{1c}) and the design variable is total area of windows (WA), then where U_P is the unit price of windows' area, the interaction between construction cost and the total area of windows, $C_{1c_{WA}}$, can be expressed as,

$$C_{1c_{WA}} = U_P \times WA \tag{3-15}$$

Based on the example, for a sub-component (j) of a criterion, C_i or C_{ij}, Step 3 involves finding f_{ijk} that regulates the relation between C_{ij} and D_k, where

$$C_{ij_k} = f_{ijk}(D_k) \tag{3-16}$$

This step should be performed for all the selected design variables with all the sub-components of all assessment criteria. Considering m_i is the number of sub-components of criterion C_i and n is the number of design variables, the number of interactions (I_i) of Step 3 for C_i is given in Equation 3-17.

$$I_i = m_i \times n \tag{3-17}$$

4. *Develop the aggregated functions for each of the assessment criteria*

The aggregated function for a criterion (C_i) is the combination of all the interactions between its sub-components and design variables. Assuming F_{Ci} denotes the aggregate function of criterion C_i, then F_{Ci} is expressed as follows:

$$F_{C_i} = \bigvee_j \bigvee_k f_{ijk}(D_k) \tag{3-18}$$

The operator, $\vee$, denotes the cumulative interaction and is defined based on the breakdown of sub-components and the relation between these sub-components and design variables.

It should be noted that the logic through which the assessment criteria are broken down into their subs-components defines the method by which the aggregated functions are formulated. In the case studies presented in the Chapter 4 (i.e., 4.1 and 4.2) the aggregated functions are considered to be the algebraic sum of the sub-components. However, various models can be used to formulate the aggregated functions such as investing functions (e.g., Net-Present Value, Return-on-Investment, etc.)

5. *Derive the aggregated functions according to each of the variables*

To provide greater practicality for the application of the framework, and to facilitate the finding of an alternative that improves the design, it is important to reduce the dimensionality of the aggregated functions by means of deriving them according to the selected design variables. This reduces the number of variables the team must deal with, while ensuring the compliance of the derived function solution with the global requirements. The derivation process follows the steps explained in Section 3.3.2.3. Where D'_{ik} denotes the derivative of the aggregated function (i) according to the design variable, D'_{ik} can be expressed as Equation 3-19.

$$D'_{ik} = \frac{\partial F_{c_i}}{\partial D_k} \tag{3-19}$$

6. *Define the technical performance measure to use and assess the design variables against one another*

As mentioned in the literature review, there are several methods to assess the potential technical performance of a system during operations. The present research, however, uses the failure model to model the behaviour of systems during operations, and uses the mean time to failure (*MTTF*) as a metric to measure the technical performance. This step includes defining the systems of which the design team desires to assess the potential technical performance during operations, followed by studying how each design variable affects this performance.

Assuming mean time to failure for design variable D_k is $MTTF_k$, this step involves defining

$$MTTF_k = f(D_1, D_2, \ldots, D_n) \tag{3-20}$$

7. *Find design options that best fit the correspondent derived functions and satisfy performance measures*

The last step in the framework is to find the design alternative that will maximize the gain from functions generated using Equation 3-19 and 3-20 for each of the design variables. There are two methods through which the design alternative can be found:

- using a utility function that measures the preference of the stakeholder toward each of the assessment criteria, and then choose the design alternative that maximizes this utility; and,

- run a multi-objective optimization (MOO) analysis on functions D'_{ik} and $MTTF_k$ for each design variable in order to find the solution that satisfies the set of functions, collectively.

More insight about the application of the framework is provided in case studies 1 and 2, which are presented in Chapter 4.

3.3. Phase 3: Developing a value-visualization framework

3.3.1 Introduction

As can be seen, the second step of the MCLCA framework states: "Define the design variables". While the MCLCA framework has no restrictions on the number of variables to consider nor on the nature of them, increasing the efficiency of the utilization implies selecting the variables with greater impact on the assessment criteria. As demonstrated in the literature, the availability of a tool that can visually assess the collective contribution of building components on the assessment criteria is vital to the success of the evaluation criteria. Therefore, this section illustrates the theoretical background and the development of the value-visualization framework that outlines the effect of design decisions collectively on multiple values as the design evolves. The concept of this framework can be explained as follows. Assuming the magnitude of contributions for two elements toward one or more values is represented as C_i and C_j, and the appearance of these elements is represented as A_i and A_j, respectively, then the following argument applies:

$$if\ C_i = C_j\ then\ A_i = A_j\ otherwise\ A_i \neq A_j$$

In other words, the framework assigns a unique appearance, in the visualization medium, for a building's elements based on their collective contribution toward the values under assessment. In this context, the framework uses BIM as the visualization medium, which also facilitates the exchange of information pertaining to a given building from and into the BIM environment. This practice, in addition to increasing the efficiency of the framework implementation, makes it viable to begin visualizing the impact of design decisions on the desired values once there is a BIM model, which can be as early as the conceptual design. Figure 3-3 presents the information flow in the proposed framework and the primary processes.

Information processing in this framework begins by assessing the various contributions of the elements toward the predefined value(s) by the stakeholders. After the contributions of the elements are assessed, the engine determines the appropriate appearance of each element, which reflects its contribution, and formulates the visualization matrix (VM), which is the repository of element appearance information based on its contribution to the values. The final step occurs when the VM is sent to the BIM model(s) to change the appearance of elements in the model(s) accordingly.

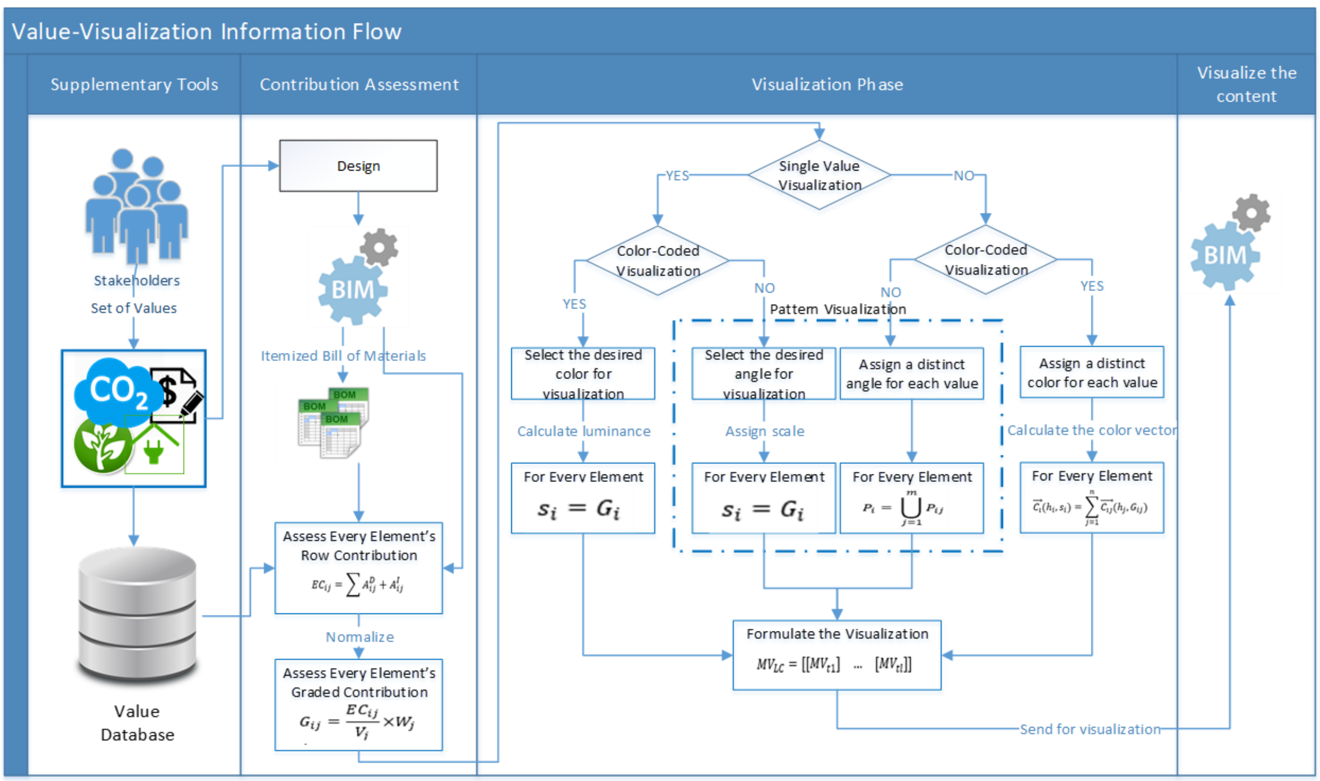


Figure 3-3 Value-visualization processes and information flow

Following this brief overview of the framework is the demonstration of the information processing required to develop a value-visualization framework.

3.3.2 Element contribution assessment phase

The backbone of the framework is assessing the magnitude of the contribution of elements to the considered value(s). Despite the added layer of complexity, one of the noteworthy components of this framework is to study the effect of building components on each of the selected values, rather than substituting all values with one representative value (such as replacing the amount of emitted CO_2 with the carbon tax cost measured by tonnes of CO_2 emission). While the number of values considered for assessment has minimal effect on the contribution assessment process, it significantly complicates the visualization process, as will be explained later. This framework performs a two-level contribution assessment: the row contribution assessment and the graded contribution assessment.

3.4.2.1 Row contribution assessment

The total effect an element has on a given value, which results from the direct or indirect influence on that value, is called the row contribution of that element to that value. Bu Hamdan et al. (2017) state that the row contribution of an element (*I*) to a value (*j*) is assessed as follows:

$$EC_{ij} = \sum I_{ij}^{D} + I_{ij}^{I} \tag{3-21}$$

where

- EC_{ij} is the row contribution of element *i* on value *j*;
- I_{ij}^{D} is the direct influence of element *i* on value *j*; and
- I_{ij}^{I} is the indirect impact of element *i* on value *j*.

Generally, assessing the direct correlation between values and a building's elements is a straightforward process, where the magnitude of this contribution is proportional to the physical attributes (e.g., the dimensions and materials) of the element. For example, where *RR*, U_c, U_s, and

U_f are the reinforcement ratio in one cubic meter of concrete, ready-mix concrete unit price, rebar unit price, and formwork unit price, respectively, and Vol_c and Sur_c are the volume and the side area of the column C, respectively, the direct influence of a concrete column (C) on cost (c) can be evaluated as follows:

$$I_{Cc}^{D} = Vol_C \times (U_c + RR \times U_s) + Sur_C \times U_f$$

For this case, the framework utilizes BIM models to extract an itemized bill of materials and links it with corresponding value databases, such as RSMeans® or BCIS® for cost, to calculate the contribution.

However, the indirect influence of elements on the studied value(s) requires further analysis that is dependent on the understanding of the interdependencies amongst the various systems that co-exist in a building, and how these interdependencies affect the performance of systems. To elaborate on this idea, consider a window in a building. Beyond the direct cost of the window, the intensity of artificial illumination required in the room is proportional to the amount of acquired natural illumination from the window, which is a function of the window size. Less necessary artificial illumination is indicative of fewer lighting fixtures, and therefore, a reduction in the direct cost of lighting fixtures and associated cost such as electrical wiring. Now, on the operational cost side, the size of the window affects the performance of the heating/cooling unit in terms of working to balance the head load that is influenced by the size of the window, which directly affects the operational cost. The analysis can go even further depending on the accuracy desired by the designers and stakeholders. Having said that, to calculate the row contribution of the windows, all the aforementioned factors should be considered. Please refer to Section 3.3.2.6 of this dissertation for further insight pertaining to this idea.

3.4.2.2 Graded contribution assessment

As different row contributions for one element have different units of measure (row contributions are not unitless; a row contribution to value *i* has the same units of measure as value *i*), having several values to visualize necessitates various methods to process the information in the succeeding phases, unless the row contributions are normalized. The normalized row contribution is called the graded contribution, which is calculated to deal with a unitless number for the element contribution to a given value.

The graded contribution of an element (*i*) to a value (*j*) is the proportion of its row contribution to the total amount of value (*j*). The graded contribution (G_{ij}) can be expressed as,

$$G_{ij} = \frac{EC_{ij}}{\sum_{i=1}^{n} EC_{ij}} \times W_j \qquad (3\text{-}22)$$

where

- EC_{ij} is the row contribution of element *i* to value *j* (see Equation 3-6); and,
- W_j is the weight assigned by stakeholders for value *j*.

It is useful for further operations to mention that the graded contribution of an element (*i*) has a vector format as follows: $\vec{G_\iota}(G_{i1}, G_{i2}, \ldots, G_{in})$. The components of the vector are the graded contribution for the element to each of the considered values.

3.3.3 Visualization phase

As previously discussed, there are several methods used by construction practitioners to support their presentations. However, the framework, proposed herein, visualizes value through changing the way in which the elements in BIM models are rendered. There are several appearance attributes such as colour, transparency, and surface pattern (Autodesk 2017). The framework uses colour and/or surface pattern changes to indicate the collective contribution magnitude of elements to the considered values. Colour-coding is selected based on the premise of familiarity, as it is widely used in various aspects of life. Therefore, people are familiar with the contextual representation and meaning of colour-coding, which makes it easier to comprehend and relate to. Nevertheless, not all people are capable of distinguishing colours, which makes colour-coding ineffective for them. To overcome this obstacle and ensure the results of value-visualizing are effective in all cases, this framework adopts another visualizing technique that changes the appearance of the element through changing their surface patterns. The calculations through which the changing of graphical representations of the element is realized are described in greater detail in the following sections.

3.4.3.1 Colour-coded visualization

In colour-coded visualization, each element is assigned a unique colour that projects its collective contribution to the studied values. In this context, it is important to begin by explaining some basic concepts pertaining to colour definition, in order that the reader can relate to the succeeding operations.

3.4.3.1.1 Colour system

Various systems exist to define, generate, and visualize colours, such as the Cyan-Magenta-Yellow-Black (CMYK) system; the Red-Green-Blue system (RGB); the Hue, Saturation, and Luminance (HSL) system; and the Munsell colour system (Levkowitz and Herman 1993; Carron and Lambert 1994). Amongst the several colour definition systems, HSL is argued to most closely replicate the way in which human eyes perceive and distinguish colours (Meyer and Greenberg

1980; Ledley et al. 1990; Levkowitz and Herman 1993). In the late 1970s, Joblove and Greenberg introduced the HSL colour space (Joblove and Greenberg 1978); in this space, a colour consists of three components, the hue, the saturation, and the luminance, through which it is defined. The hue is the dominant wavelength (Kulathilake 2015) and is measured by the angle between the colour vector and the vector that represents red, which has a hue of 0°, in the chosen plane; the hue ranges between 0° and 360°. The saturation (or chroma) of the colour is a measure for the colour fullness (Joblove and Greenberg 1978) or amount of white present in the colour (Kulathilake 2015), ranging between 0 and 1. The luminance/intensity (or value, as proposed by Joblove and Greenberg (1978) as presented in Figure 3-4) reflects the brightness of the colour; for black, the luminance is 0, and it is 1 for white. See Figure 3-4 for the representation of the colour space.

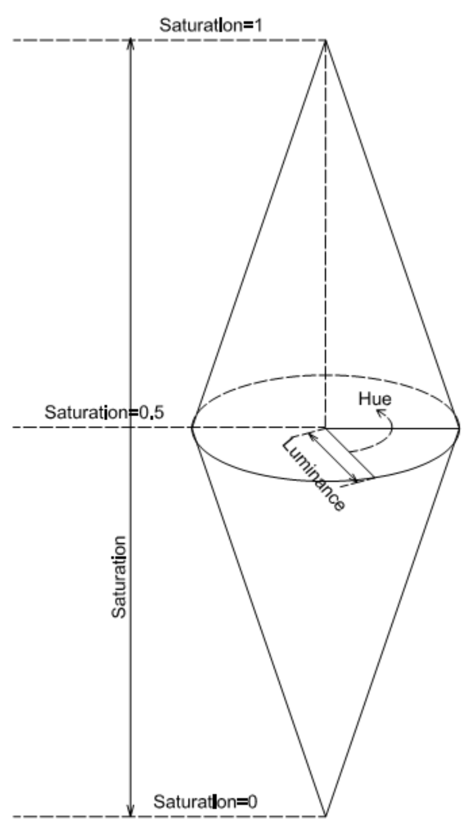


Figure 3-4 The colour space as proposed by Joblove and Greenberg (1978)

In fact, there is an infinite number of colours that could be generated from each panel in colour space, due to the infinite number of combinations for the hue, saturation, and luminance. Reducing the number of colour components to be defined (i.e., rather than defining the three colour components, consider one as constant) will significantly reduce the effort required for colour definition. The colour wheel presented in Figure 3-5, which people are generally familiar with, is the result of fixing the saturation to the value of 0.5 (or 50%). In this plane, the colour is defined through only two components, the hue and the luminance, and can be represented as $\overrightarrow{C_\iota}(h, l)$, where ($h$) is the hue—the angle this vector makes with the red vector, and (l) is the luminance of the colour. Note that all colour vectors in this plane intersect at one point. This colour plane will be used by the proposed visualization framework for colour generation, and therefore, the multi-dimensional graded contribution vector of an element will be replaced with a two-dimensional colour vector within this plane (see Figure 3-5).

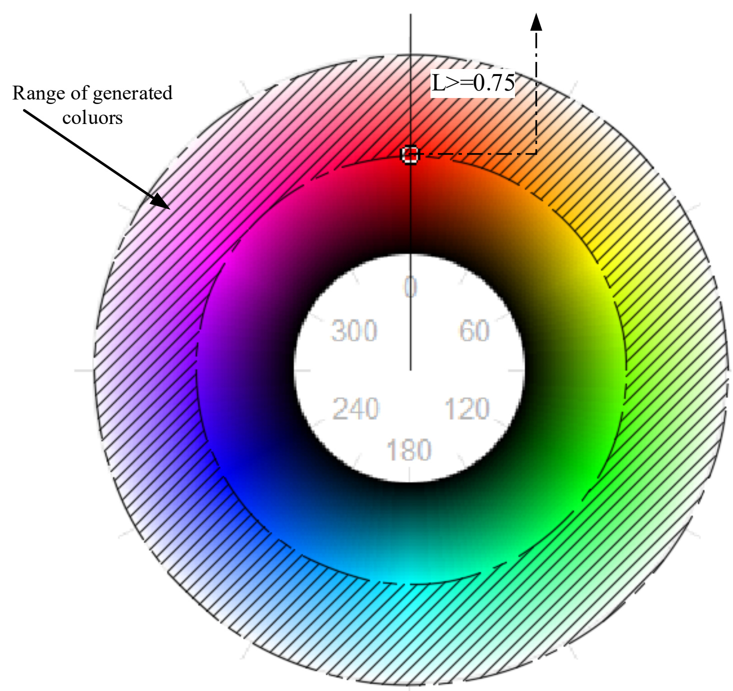


Figure 3-5 Colour wheel and colour generation range

In this plane, red, yellow, green, cyan, blue, and magenta are defined as $\overrightarrow{C_R}(0,0.5)$, $\overrightarrow{C_Y}(60,0.5)$, $\overrightarrow{C_G}(120,0.5)$, $\overrightarrow{C_C}(180,0.5)$, $\overrightarrow{C_B}(240,0.5)$, and $\overrightarrow{C_M}(300,0.5)$, respectively.

3.4.3.1.2 Single-value visualization

Intrinsic value visualization is common practice in the construction industry; the contours of slab deflection under the effect of design loads and heat loss graphs are widely used and constitute good examples for performance (an intrinsic value) visualization. The work of Bertoni et al. (2013), as mentioned in the literature review, represents another example for single-value visualization, where cost is being visualized.

Although this framework is developed to support multiple-value visualization, it offers the possibility to demonstrate the interaction between building components and the selected value. To deliver this feature, the process begins by assigning a base colour to represent the value; in the plane defined previously, this colour can be written as $\overrightarrow{C_V}(h_v, 0.5)$[4]. The elements in the BIM models will be assigned the same hue as the value colour, while the luminance of colour assigned to the element will represent the magnitude of its contribution to the studied value. It is noteworthy to mention here that the colours generated in the used plane and their luminance, $l \in [0,0.5]$, are darker and more difficult to distinguish. Therefore, the generation of the colour will be restricted with the domain where $l \in [0.5, 1]$. Based on this, the proposed framework considers the luminance value of the element's corresponding colour as inversely-proportional to its contribution. In other words, if the contribution is high, the luminance is low, and the colour

[4] The luminance here is set to begin with colours that are easily recognizable by the users, such as red, yellow, green, and blue.

component values are nearer to h_v and 0.5; as the colour fades to white, the contribution nears zero. As such, the colour vector components of an element are expressed as follows:

$$l_i = 1 - 0.5 \times G_{ij} \qquad (3\text{-}23)$$
$$h_i = h_v$$

3.4.3.1.3 Multiple-value visualization

The challenge associated with multiple-value visualization arises from the need to assign only one colour to every element, which depicts its collective contribution to all the values under assessment. This process can be understood as a projection problem for the contribution vector of an element (i) onto the plane v = 0.5 in the colour space, and can be expressed as,

$$\overrightarrow{G_\iota}(G_{i1}, G_{i2}, \dots, G_{in}) \xrightarrow{transform} \overrightarrow{C_\iota}(h_i, s_i) \qquad (3\text{-}24)$$

To perform this transformation, the framework follows four steps, which are described below.

- Assign a colour for each value in the value set and obtain the corresponding hue (see Table 1 for the major colours), then the colour vector of a value (j) is defined as $\overrightarrow{C_J}(h_j, 0.5)$.
- For each component, G_{ij}, of $\overrightarrow{G_\iota}$, create a vector $\overrightarrow{C_{\iota J}}(h_j, G_{ij})$.
- Calculate the intermediate colour vector for element i as per Equation 3-25.

$$\overrightarrow{C^{inter}}_{\iota}(h_i^{inter}, l_i^{inter}) = \sum_{j=1}^{n} \overrightarrow{C_{\iota J}}(h_j, G_{ij}) \qquad (3\text{-}25)$$

- Calculate the components of the colour vector for element i in the colour space as per Equation 3-26.

$$l_i = 1 - 0.5 \times l_i^{inter} \qquad (3\text{-}26)$$
$$h_i = h_i^{inter}$$

To understand the rational indication of the colour assigned to the element in multiple-value visualization, consider the colour wheel presented in Figure 3-6.

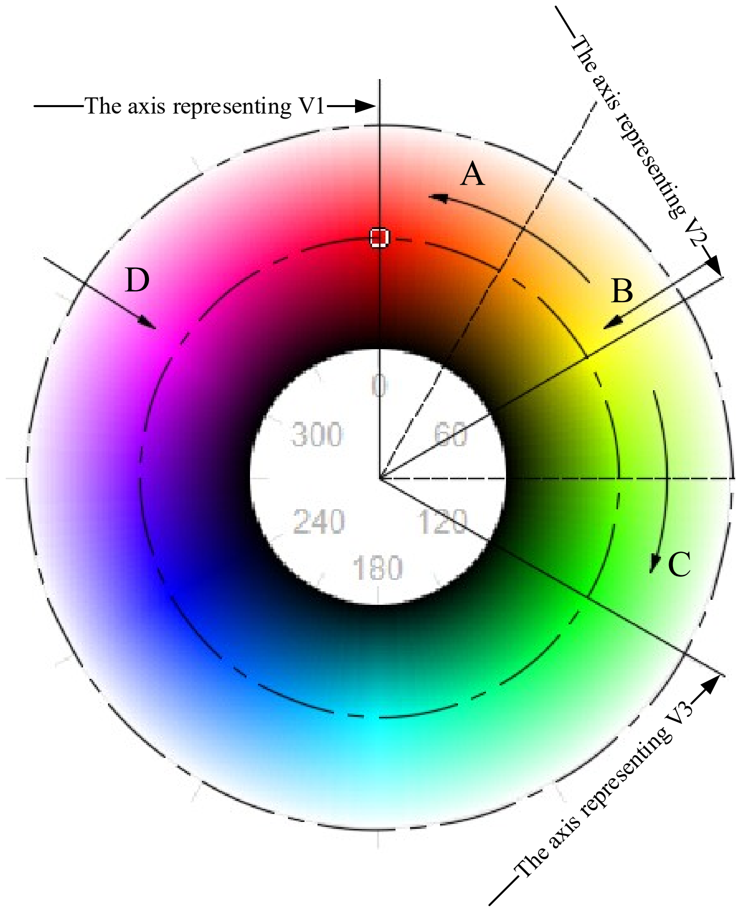


Figure 3-6 Colour interpretation in the framework

As the colour of the element follows in the D direction, the magnitude of the collective contribution of elements to the values assessed by the framework is increasing in intensity. Now, if the values to be evaluated are V1, V2, and V3 and they are assigned the colours indicated in Figure 3-6, Table 3-1 presents an explanation of the possible scenarios.

Table 3-1 Scenario interpretations

Scenario	Interpretation
The colour is leaning in direction A	The element primarily contributes to V1
The colour is leaning in direction C	The element primarily contributes to V3
The colour is near the V2 axis and leaning in direction B	The element primarily contributes to V2
The colour is near the V2 axis and leaning opposite of direction B	The element has similar contribution to all values

3.4.3.2 Pattern-based visualization

This framework offers a colour-neutral method of presenting data by providing various pattern styles. Pattern-based visualization is a viable option for value visualization, and there are several patterns that can be used for this purpose. However, to avoid potential difficulties related to distinguishing the combinations of several patterns, the framework uses parallel lines for values. The parallel line pattern can be defined as a function of the scale that defines the spacing between the lines and the angle the lines make with the horizon:

If α is the angle of the lines where $\alpha \epsilon [0,180[$, and *Sc* is the scale where $Sc \epsilon]0,100]$, then the pattern is

$$P = f(\alpha, Sc) \tag{3-27}$$

As with the colour-coding scheme, each value is assigned only one pattern. In this context, the angle indicates the value, while the scale represents the magnitude. For single-value visualization, the angle remains the same for all the elements, while the scale changes according to the given element's contribution to the studied value (in a similar manner to the luminance). This can be expressed as,

$$Sc_{ij} = 100 \times (1 - G_{ij}) \tag{3-38}$$

The pattern of element i for value j is expressed as per Equation 3-29

$$P_{ij} = f(\alpha_j, Sc_{ij}) \tag{3-29}$$

In multiple-value visualization, multiple pattern angles are displayed on the same element, each representing a distinct value. For a given value, the angle of the pattern is defined according to the corresponding value (i.e., graded value) it represents, while the scale maintains the same representation. Unlike the complexity in finding the correct representative colour, visualizing multiple values using pattern style is relatively easy, and the resultant pattern can be expressed as follows (see Figure 3-7, for example):

$$P_i = \bigcup_{j=1}^{m} P_{ij} \tag{3-30}$$

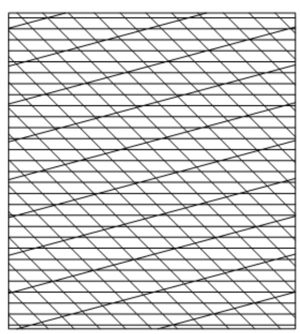


Figure 3-7 Pattern P, where P = (0,5) ∪ (45,3) ∪ (60,10)

3.4.3.3 Lifecycle visualization and visualization matrix

As the building progresses through the various phases during its life span (from conceptual design to demolition), the magnitude of influence the elements have on the values changes. For example, at the end on the construction phase the structure of the building contributes the most to the carbon footprint. The magnitude of this contribution begins to decrease once the operation phase begins, as the HVAC systems begins emitting carbon gases, making them the major contributors to the carbon footprint of the building. Therefore, understanding the interaction between building components and values throughout the building lifecycle is vital for better decision-making pertaining to value-adding during design.

Having said that, the value visualization provides a time-lapse visualization of the elements' influence on studied values throughout the building life span. The length of the intervals at which the influence of the elements is assessed determines the visualization type. In this context, there are two types of visualization: (1) continuous, where the intervals between the instants approach zero; and (2) discrete, where the values are assessed at instants (with constants or variable intervals) during the life span of the building.

This leads to the introduction of the concept of the visualization matrix, which can be defined as the repository of the appearances of all elements at all time points. Assuming t_i is an event in a building lifecycle, and V_i is the graphical appearance (colour-coded and/or surface pattern) of element i at t_i, then the graphical appearance of all elements at that given event can be written as,

$$MV_t = \begin{bmatrix} V_1 \\ \vdots \\ V_n \end{bmatrix} \tag{3-31}$$

The visualization matrix (MV_{LC}) for the entire lifecycle of the project is expressed as Equation 3-32.

$$MV_{LC} = [[MV_{t1}] \quad \ldots \quad [MV_{tl}]] \tag{3-32}$$

This matrix communicates the changes in appearance of the elements in the BIM models during the lifecycle of the building.

4. Case Studies

4.1. Case Study 1: the application of the Multi-criteria Lifecycle Assessment design framework

This case study explores the utilization of the MCLCA framework to improve the design of a single-family house. For this case study, 18 variables are subject to change to reduce the lifecycle cost, lifecycle energy consumption, and lifecycle carbon emissions while maintaining the technical performance (i.e., MTTF) of the HVAC system. The house has a total area of 3,333 ft^2 distributed among two storeys and a basement, as presented in Table 4-1.

Table 4-1 Area breakdown of Case Study 1 house

Floor	Area (ft^2)
Basement	1,068
Ground Floor	1,088
First Floor	1,177

To provide a better understanding of the shape of the house used in the case study, Figure 4-1 presents a 3D rendering view of the building. The floor plans of the case study house are presented in Appendix A. Note that this BIM model is used to retrieve information pertaining to material quantities that will be used to assess the impact of design on the assessment criteria (i.e., lifecycle cost, lifecycle energy consumption, and lifecycle carbon emissions).

Figure 4-1 3D rendering of Case Study 1 house

The application of the framework follows the work break-down structure (WBS) presented in Figure 4-2.

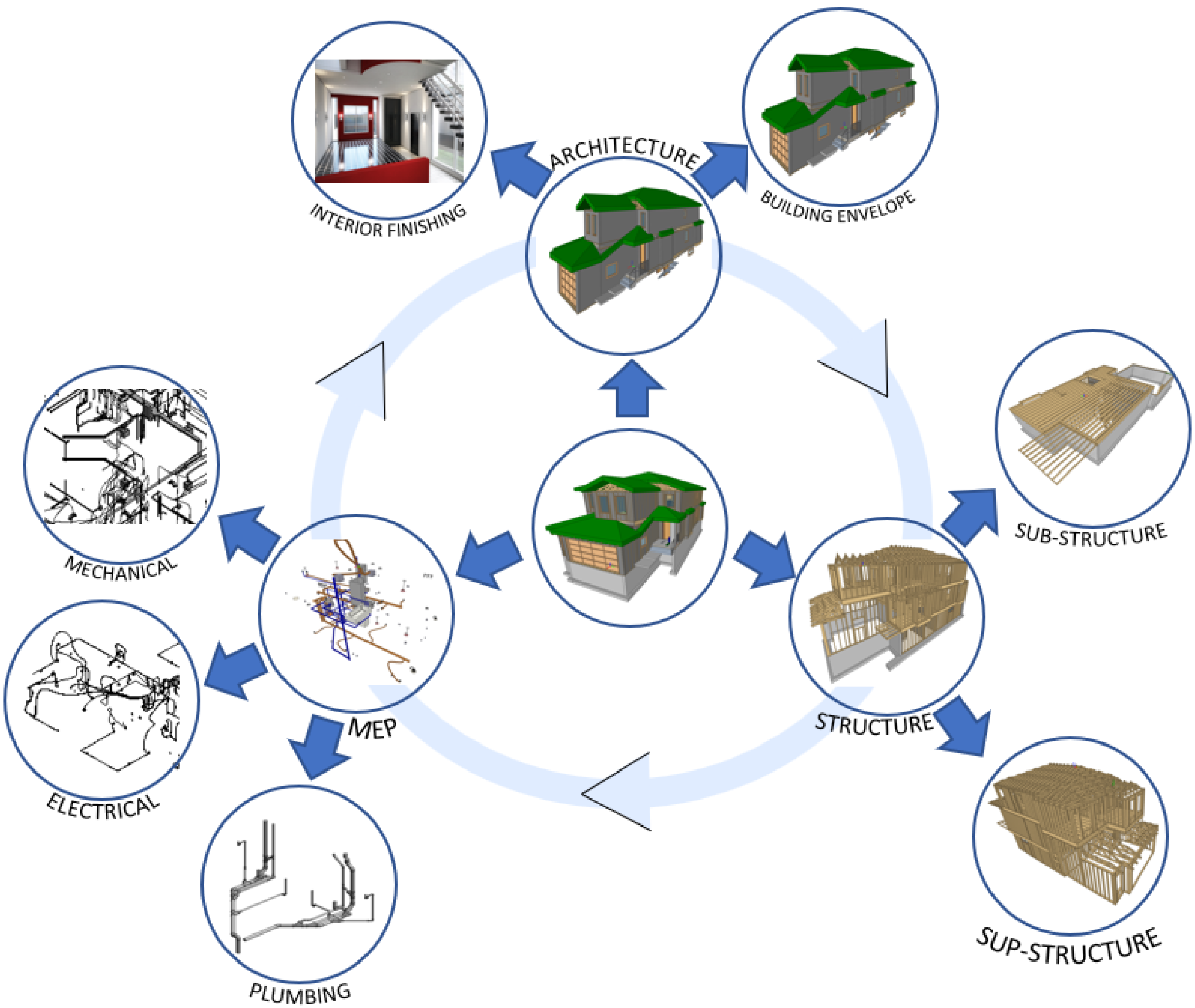


Figure 4-2 WBS of Case Study 1 house

The structural system includes the following components:

- Sub-structure

    The basement is bounded by 9-ft concrete walls in the form of foundation walls resting on wall-foundation type footings. Additionally, there are 3 pad footings supporting the posts in the basement.

- Super-structure
  - Floors: loads are transferred horizontally through a set 2×14 wooden joists that are resting on load bearing walls.
  - Walls: a set of load bearing walls are distributed throughout the floor plan with 2×8 16″ O.C. studs. The remainder of the walls are 2×4 16″ O.C. studs for partition walls, and 2×6 16″ O.C. studs for exterior wall.
  - Roof: the structural system of the roof consists of wooden trusses located every 24″.

According to the original design, the architectural systems include:

- Building envelope, which can be broken down as follows:
  - double glazed windows, distributed between the three floors as presented in Table 4-2.

Table 4-2 Windows sizes and locations

Window Size (in ft)	Number of Windows per Floor		
	Basement	Ground	First
5×2	2	0	0
2×5	0	1	0
3×3	0	1	0
3×5	0	1	4
3×6	0	6	0
2×3.5	0	0	2
2.5×5	0	0	2
3×4.5	0	0	5
3×4	0	0	1
4×4	0	0	1

Window-to-wall ratio (WWR) of a façade (i) is calculated as Equation 4-1 states:

$$WWR_i = \frac{\sum_{j=1}^{n} WA_{ij}}{\sum_{k=1}^{m} WlA_{ik}} \tag{4-1}$$

where WA_{ij} represents the area of window j on façade I; and WlA_{ik} represents the area of wall k on façade i.

Based on Equation 4-1, information in Table 4-2, and drawings in Appendix A, the WWRs of the given design are presented in Table 4-3.

Table 4-3 WWR for each of the facades

Façade	WWR
Northern	0.037
Western	0.276
Eastern	0.117
Southern	0.017

- 24-R-value walls, which consist of a layer of exterior finishing (as per architectural specifications), building wrap, ½″ sheathing, wooden studs, R20 batt insulation, vapour barrier (6 mm), and a final layer of interior finished and painted gypsum board.
- 36-R-value roof, which includes 7/16″ sheathing, wooden trusses (as stated in the structural specifications), R34 batt insulation, vapour barrier (6 mm), and a layer of ½″ drywall.

- Interior finishing, which as per the design specifications for the house, include:
  - Passage & closet doors—paint grade raised panel style doors.
  - Door hardware—antique nickel or chrome.
  - Baseboards—4 ¼″ painted MDF

- Door & window casings—3 ½″ painted MDF
- Shelving—constructed of MDF
- Carpet—100% nylon cut pile or Berber with #7 underlay.
- Hardwood, carpet, tile on main floor and bathrooms
- Paint—1 wall colour and 1 trim colour
- 1 coat of primer and 2 coats of latex finish on walls in all areas
- Interior doors and trim to be painted with latex semi-gloss finish
- Framed mirrors with Italian wood moldings
- Maple railing with iron rods.

The MEP systems have a proposed design as follows:

- HVAC system (a general ASHRAE Package System is used). This system includes the following components:
  - Gas-fired hot water boiler with draft fan >2,500 kBtu•h, 84.5% combustion efficiency
  - Variable volume hot water pump
  - Hot water coil
  - Variable volume chilled water pump
  - Chilled water coil
  - Variable volume condenser water pump
  - Domestic hot water unit (0.575 Energy Factor)
- Plumbing system specifications include:
  - Waterlines: home run system
  - Minimum 141 L (50 US Gallon) hot water tank

- Roughed-in double plumbing
- Kitchen sink: double stainless steel (under mount) with single lever chrome faucet
- Hose bibs as per plan
- Gas line to garage, kitchen, and a future deck.
- Vanity sinks: white with single lever chrome faucet
- Toilets: white china
- Tubs: white fibreglass 1-piece tub/shower combo, master bath set-up with tub option
- Roughed in dishwasher
- Shut-off valve on each tap
- Water line to fridge
- Garage hot and cold taps
- Floor drain in laundry room

- And, finally, the electrical system is designed to include the following:
    - 100-amp circuit panel—minimum 30-60 circuits
    - Telephone—5 outlets (as per plan)
    - Cable outlets—4 outlets
    - Standard lighting package as per plan
    - Roughed-in central vacuum system with 2 outlets for future use
    - Smoke detectors wired to house electrical system—all rooms as per code
    - Decorah Plugs and Switches—all bedrooms GFI as per code
    - LED under cabinet lighting

The following sections will detail the application of the framework proposed in Section 3.3.5.

1. *Define the sub-components of the assessment criteria*

As defined earlier, the assessment criteria used in the present research are cost (*C*), energy consumption (*EC*), and carbon emissions (*CeM*). Given that the proposed framework aims to evaluate the building over its lifecycle, it is possible to summarize the lifecycle of the building in two phases: the construction phase that spans between the conceptual design phase and the commissioning phases, and the operation phase that spans between commissioning and demolishing (see Figure 4-3).

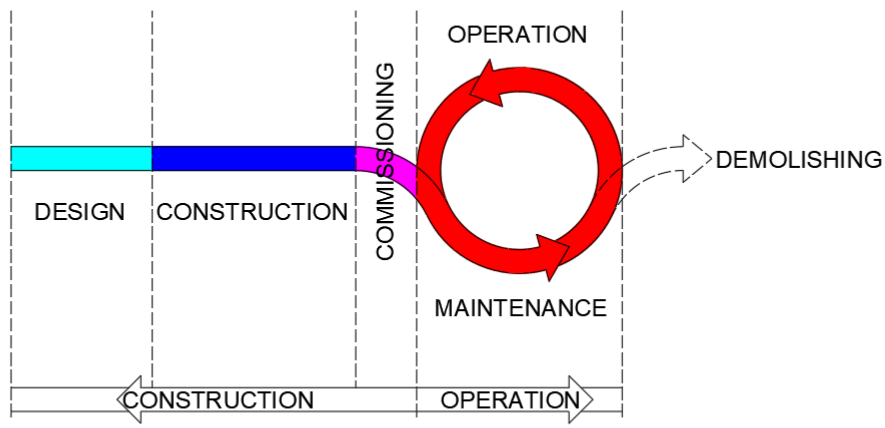


Figure 4-3 Lifecycle phases of a project

Based on the lifecycle breakdown, the assessment criteria can be broken down into two subcomponents that align with the building lifecycle phases as follows.

- Cost (*C*) can be seen as the sum of the construction cost (C_{con}) and operational cost (C_{ops}) as expressed in Equation 4-2

$$C = C_{con} + C_{ops} \tag{4-2}$$

- Energy Consumption (*EC*) signifies the sum of the operational energy (EC_{ops}), which represents the energy consumed during the operational phase of the building lifecycle, and the energy consumed during the construction of the house, which is usually referred to as embodied energy (EC_{emb}). *EC*, therefore, can be assessed as,

$$EC = EC_{emb} + EC_{ops} \tag{4-3}$$

- Carbon Emission (CeM) also has two sub-components: emitted carbon (CeM_{ops}) that measures the amount of carbon the house produces during the operation phase, and the carbon footprint (CeM_{fp}) that assesses the carbon produced due to the construction of the house. Therefore, CeM can be expressed as,

$$CeM = CeM_{fp} + CeM_{ops} \tag{4-4}$$

Figure 4-4 presents the assessment criteria and their breakdown structure according to the lifecycle phases.

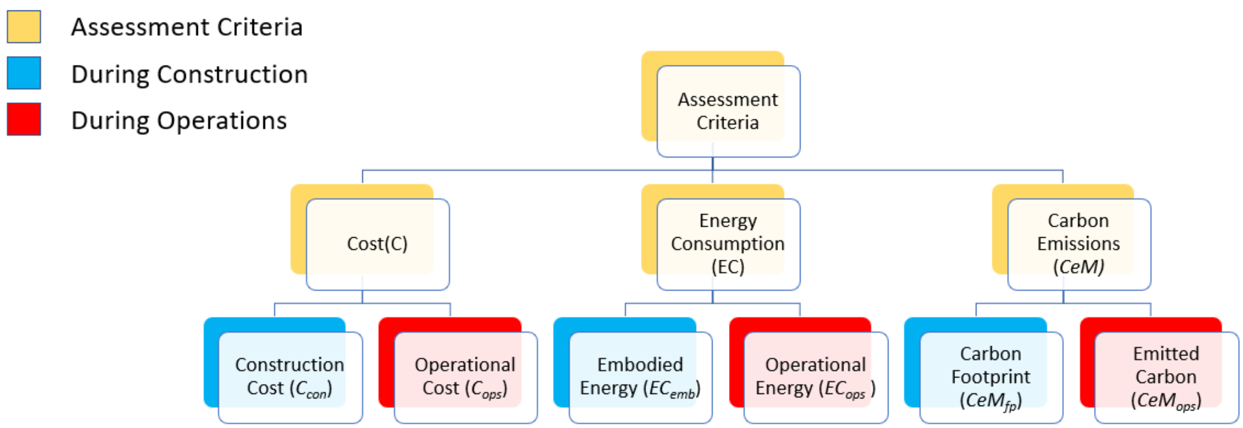


Figure 4-4 Criteria breakdown structure (CBS)

2. *Define the design variables*

Given that there is no generative engine supporting the application of the framework, the architectural design pertaining to space allocation and area shall not be considered as a variable, nor shall the components that will significantly affect the space layout (e.g., switching to a grid of columns for vertical load transfer rather than the current load-bearing walls). The variables can be categorized into the following streams (in alignment with the building systems):

- architectural variables: building orientation (*BO*) measured in degrees, where $BO \in \{0, 45, 90, 135, 180, 225, 270, 315\}$;
- structural variables: construction material (*CM*) super-structure systems, where $BO \in \{Wood, light\ steel\}$;
- building envelope variables: window type (*WT*), which can be single, double, or triple (see Figure 4-5); window shade (*WSH*), which takes one of the following values: no shade, one-third shaded, or two-thirds shaded); window-to-wall ratio (WWR) (note that *WT*, *WSH*, and WWR are assessed for each façade); R-Value for walls (WRV); R-Value for roof (RRV); and,
- HVAC systems type, which can be one of the following (the components of each system can be found in Appendix B):
    - High Efficiency Heat Pump (HVAC1)
    - ASHRAE Heat Pump (HVAC2)
    - High Efficiency Package System (HVAC3)
    - ASHRAE VAV (HVAC4)
    - High Efficiency VAV (HVAC5)
    - ASHRAE Package Terminal (HVAC6)
    - High Efficiency Package Terminal AC (HVAC7)

Figure 4-5 Glazing styles of windows

As noted previously, the variables related to windows are assessed for each of the façades, which implies using different notations as per façade. Table 4-4 demonstrates the notations used for these cases.

Table 4-4 Variables used in Chapter 4 and their corresponding acronyms

Variable	Acronym
Window-to-wall ratio on the north façade	N-WWR
Window-to-wall ratio on the east façade	W-WWR
Window-to-wall ratio on the west façade	E-WWR
Window-to-wall ratio on the south façade	S-WWR
Window shading on the north façade	N-WSH
Window shading on the east façade	W-WSH
Window shading on the west façade	E-WSH
Window shading on the south façade	S-WSH
Window type on the north façade	N-WT
Window type on the west façade	W-WT
Window type on the east façade	E-WT
Window type on the south façade	S-WT

3. *Define the interactions between the design variables and the sub-components of the assessment criteria*

- **Define the interactions during the construction phase**
    - The interactions between the design variables and construction cost*:*

Considering the quantity of a building element (*i*) is Q_i measured as per the industry practice (e.g., ft^2 for the drywall sheets), and UP_i is the unit price of the element (*i*), the total construction cost of the building can be written as,

$$C_{con} = \sum_{i=1}^{n} Q_i \times UP_i \tag{4-5}$$

As per Equation 4-5, the total construction cost of the house used for the case study is CA$443,617.00. The detailed cost estimation can be found in Appendix C.

To explicitly present Equation 4-5 as a function of design variables, based on the information in Appendix C it is possible to write:

$$C_{con} = Q_{CM_{studs}} \times UP_{CM_{studs}} + Q_{CM_{joist}} \times UP_{CM_{joist}} + Q_{CM_{truss}} \times UP_{CM_{truss}} + \sum WWR_i \times WA_i \times UP_{WT} + UP_{WRV/SF} \times \sum FA_j + UP_{RRV/SF} \times RFA + C_{con_{HVAC}} + 275{,}740.49 \tag{4-6}$$

Note that the constant (CA$275,740.49) in Equation 4-6 is calculated by subtracting the cost of items corresponding to the design variables from the overall construction cost. In Equation 4-6, the following applies:

- $Q_{CM_{studs}}, Q_{CM_{joist}}, Q_{CM_{truss}}$ denote the quantity of construction materials that exist in the wall studs, floor joists, and roof trusses, respectively.

- $UP_{CM_{studs}}, UP_{CM_{joist}}, UP_{CM_{truss}}$ denote the unit price of the construction materials of studs, joists, and trusses, respectively.
- $i \in \{Northern\ Facade, Western\ Facade, Eastern\ Facade, Southern\ Facade\}$
- $UP_{WRV/SF}$ denotes the cost of insulating 1 ft^2 of the house to achieve a certain WRV (e.g., to insulate the wall to an R-value of 32 it costs CA\$3.01/ft^2).
- FA_j denotes the area of floor (*j*), where $j \in \{Ground\ Floor, First\ Floor\}$
- $UP_{RRV/SF}$ denotes the cost of insulating 1 ft^2 of roof footprint to achieve a given RRV.
- RFA denotes the footprint area of the roof.
- $C_{con_{HVAC}}$ denotes the construction cost of HVAC systems, and will be assumed to be equal for all alternatives.
    - The interactions between the design variables and embodied energy*:*

Considering the quantity of construction materials of a building element (i) is QM_i, measured as per the industry practice (e.g., ft^2 for drywall sheets), and UEE_i is the embodied energy in 1 unit of element *i* material, the total embodied energy of the building can be written as,

$$EC_{emb} = \sum_{i=1}^{n} QM_i \times UEE_i \qquad (4\text{-}7)$$

As per Equation 4-7, using the information about UEE provided by ICE database (Circular Ecology 2011), the total embodied energy of the house used for the case study is 1.8×10^6 MJ. Based on Equation 4-7, the embodied energy as a function of the design variable can be expressed as Equation 4-8.

$$EC_{emb} = Q_{CM_{studs}} \times UEE_{CM_{studs}} + Q_{CM_{joist}} \times UEE_{CM_{joist}}$$
$$+ Q_{CM_{truss}} \times UEE_{CM_{truss}} + \sum WWR_i \times WA_i \times UEE_{WT}$$
$$+ \ UEE_{WRV/SF} \times \sum FA_j + UEE_{RRV/SF} \times RFA + EC_{emb_{HVAc}}$$
$$+ 1.3 \times 10^6 \tag{4-8}$$

The constant (1.3×10^6 MJ) in Equation 4-8 is calculated by subtracting the contribution of items correspondent to the design variable to the embodied energy from the overall embodied energy. In Equation 4-8, note the following:

- $UEE_{CM_{studs}}, UEE_{CM_{joist}}, UEE_{CM_{truss}}$ denote the amount of embodied energy in 1 unit of the construction materials of studs, joists, and trusses, respectively.
- $UEE_{WRV/SF}$ denotes the amount of embodied energy associated with insulating 1 ft^2 of the house to achieve a certain WRV.
- $UEE_{RRV/SF}$ denotes the amount of embodied energy associated with insulating 1 ft^2 of roof footprint to achieve a given RRV.
- $EC_{emb_{HVAc}}$ denotes the amount of embodied energy associated with the installation of the HVAC systems, and will be assumed to be equal for all alternatives.
    - The interactions between the design variables and embodied carbon:

Assessing the embodied carbon is identical to assessing the embodied energy with the exception of using the embodied carbon in 1 unit of element *i* material, UEC_i, rather than of UEE_i. Therefore, the total embodied carbon of the building can be written as,

$$CeM_{fp} = \sum_{i=1}^{n} QM_i \times UEC_i \tag{4-9}$$

ICE database is also used to find the amount of embodied carbon associated with 1 unit of construction material, which as per Equation 4-9 leads to a total of 98 t of embodied carbon associated with the construction of the house.

As can be seen in the discussion presented prior to forming Equation 4-9, Equation 4-9 can be reintroduced as Equation 4-10:

$$\begin{aligned} CeM_{fp} = {} & Q_{CM_{studs}} \times UEC_{CM_{studs}} + Q_{CM_{joist}} \times UEC_{CM_{joist}} + Q_{CM_{truss}} \times UEC_{CM_{truss}} \\ & + \sum WWR_i \times WA_i \times UEC_{WT} + UEC_{WRV/SF} \times \sum FA_j \\ & + UEC_{RRV/SF} \times RFA + CeM_{emb_{HVAc}} + 70 \end{aligned} \tag{4-10}$$

70 (metric tonnes) is the constant that results from excluding the items related to the design variables when calculating the total embodied carbon. In Equation 4-10:

- $UEC_{CM_{studs}}, UEC_{CM_{joist}}, UEC_{CM_{truss}}$ denote the amount of embodied carbon in 1 unit of the construction materials of studs, joists, and trusses, respectively.
- $UEC_{WRV/SF}$ denotes the amount of embodied carbon associated with insulating 1 ft^2 of the house to achieve a certain WRV.
- $UEC_{RRV/SF}$ denotes the amount of embodied energy associated with of insulating 1 ft^2 of roof footprint to achieve a given RRV.
- $CeM_{emb_{HVAc}}$ denotes the amount of embodied energy associated with the installation of the HVAC systems, and will be assumed to be equal for all alternatives.
- **Define the interactions during the operation phase**

Before proceeding with the definition of the interactions, it is useful to provide a background about energy demand calculations, as it is central to the interaction evaluation. The method to calculate the heating and cooling loads herein is as prescribed by the 2015 ASHRAE handbook: heating, ventilating, and air-conditioning applications (ASHRAE 2015), which considers the hourly heat demand (Q) as the sum of the internal heat gain (Q_{int}), heat gain and/or loss through ventilation and infiltration (Q_{ven}), heat gain and/or loss through fenestration area (Q_{fen}), and heat gain and/or loss through opaque areas (Q_{opa}), as presented in Equation 4-13.

$$Q = Q_{int} + Q_{ven} + Q_{fen} + Q_{opa} \tag{4-13}$$

A negative value for Q indicates that space heating is required, while a positive value indicates the need for cooling.

Calculating Q_{int} requires quantifying the heat generated by the following: (1) potential occupants (HG_p), (2) lighting fixtures (HG_l), and (3) existing appliances and/or equipment (HG_{eq}), where,

$$Q_{int} = HG_p + HG_l + HG_{eq} \tag{4-14}$$

Information concerning how to quantify internal heat gain can be obtained from Chapter 14 of the ASHRAE 2015 handbook noted above (ASHRAE 2015). However, in regard to HG_p and HG_{eq}, it should be noted that they are independent from the selected design variables. HG_l, on the other hand, is indirectly related to *WWR, WT, WSH*, and *BO*, as these variables control the amount of natural illumination shining into the house, and, therefore, the demand for artificial lighting. However, the LED lighting fixtures required by the design of this house have negligible heat generation (Petroski 2002). This interdependency between HG_l, from one end, and *WWR, WT, WSH*, and *BO* from the other, thus, can be ignored. The heat gain and/or loss through ventilation and infiltration (Q_{ven}), on the other hand, is a function of the size of the conditioned space and the tightness of the building envelope (ASHRAE 2013), which indicates that it is not related to the selected variable and can be disregarded.

To calculate Q_{fen}, information pertaining to climate should be assessed first, then the findings can be used to calculate Q_{fen}. Figure 4-6 presents the process to calculate Q_{fen} and the necessary climate information. Climate design information is related to the geographical location of the building, and therefore, it is independent from all the selected design variables.

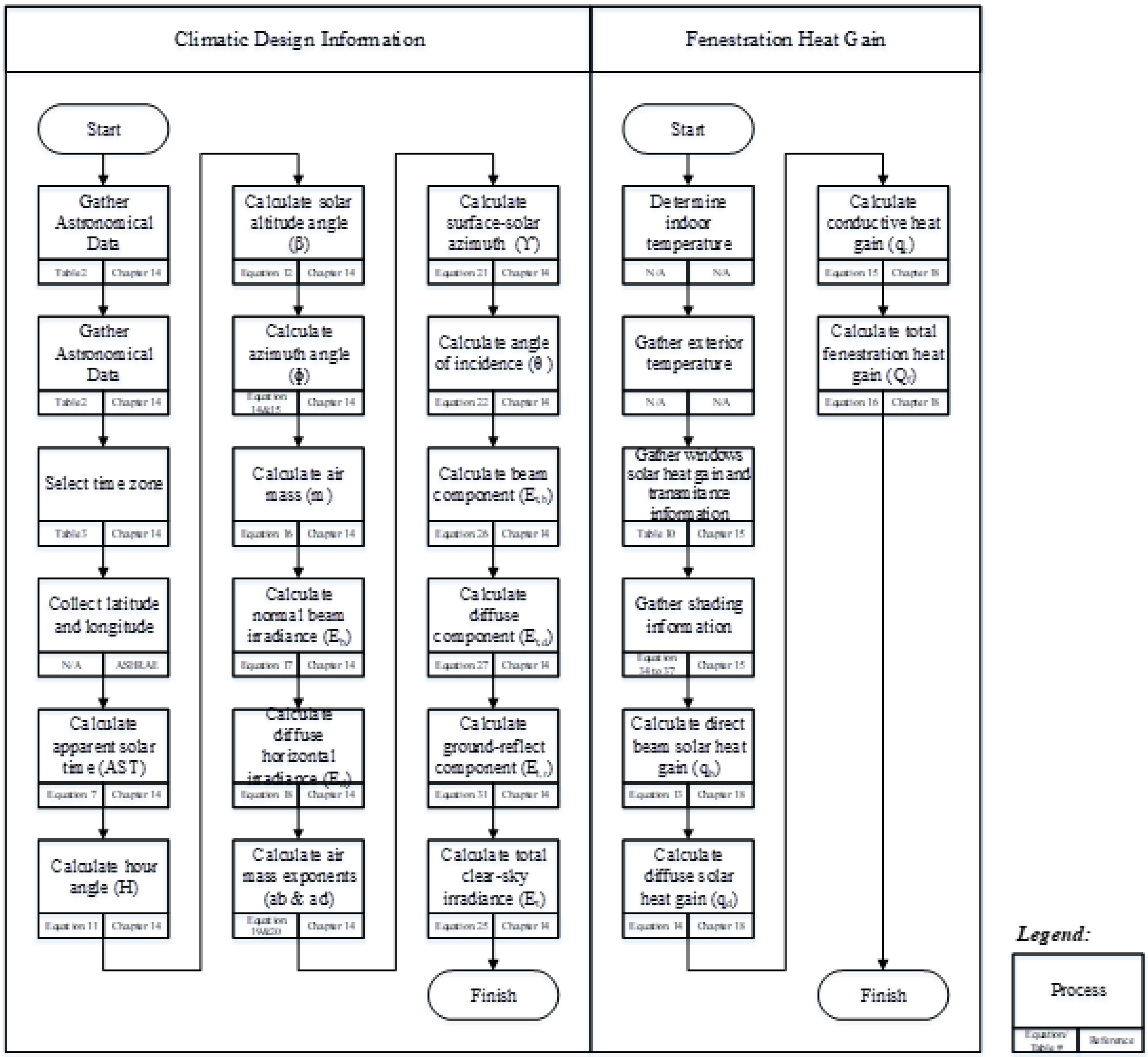


Figure 4-6 Calculating the Heat gain/loss through fenestration)

As per the 2015 ASHRAE Handbook, Q_{fen} is calculated as follows:

$$Q_{fen} = \sum_{i=1}^{n} (U_i A_{pf_i}(t_{out} - t_{in}) + (SHGC_i) A_{pf_i} E_t + (AL) A_{pf_i} \rho C_p (t_{out} - t_{in})) \tag{4-15}$$

where

U_i represents the overall coefficient of heat load (U-factor which is the inverse of R-value) for element i, W/ (m^2. K)

A_{pf_i} represents the total projected area of fenestration for element i, m^2

t_{in} denotes the indoor temperature, ^oC

t_{out} denotes the outdoor temperature, ^oC

$SHGC_i$ represents the solar heat gain coefficient for element i, dimensionless

E_t represents the incident total irradiance, W/ m^2

AL represents the air leakage at the current conditions, m^3/ (s. m^2)

ρ represents the air density, kg/m^3

C_p represents specific heat of air, kJ/kg.K

The value of U_i is dependent on the number of the layers in the element, material properties of each layer, the area of the frame and its material properties, and the area of the opening, where it can be calculated as per Equation 4-16.

$$U_i = \frac{U_{cg_i} \times A_{cg_i} + U_{eg_i} \times A_{eg_i} + U_{f_i} \times A_{f_i}}{A_{pf_i}} \tag{4-16}$$

where *cg*, *eg*, and *f* denote properties in the center of the glass, edge of the glass, and the frame, respectively.

Considering the properties of glass are equal in the center and on the edges of the windows, Equation 4-16 can be rewritten as follows:

$$U_i = \frac{U_{g_i} \times A_{g_i} + U_{f_i} \times A_{f_i}}{A_{pf_i}} \tag{4-17}$$

Note that the design variable *WT* controls the number of layers of glass in the window, which changes the thermal properties of the glazed area. Therefore, it is possible to write

$$U_{g_i} = f(WT) \tag{4-18}$$

If α represents the percentage of glazed area, then

$$A_{g_i} = \alpha A_{pf_i} \tag{4-19a}$$

$$A_{f_i} = (1 - \alpha) \times A_{pf_i} \tag{4-19b}$$

A_{pf} is related to *WWR*, where, as per Equation 4-1, A_{pf} for a façade (i) can be calculated as follows:

$$A_{pf} = WWR_i \times \sum_{j=1}^{n} WA_{ij} \tag{4-20}$$

where n is the number of walls on that façade.

Now, assuming that all the windows used on the same façade have the same α, glass material, and frame material, then based on Equations 4-18, 4-19a, 4-19b, and 4-20, U-factor of a façade (i) can be calculated as follows:

$$U_i = \frac{f(WT) \times \alpha \times WWR_i \times \sum_{j=1}^{n} WA_{ij} + U_{f_i} \times (1 - \alpha) \times WWR_i \times \sum_{j=1}^{n} WA_{ij}}{WWR_i \times \sum_{j=1}^{n} WA_{ij}} \tag{4-21}$$

As per 2015 ASHARE, SHGC for fenestration (i) is calculated as per Equation 4-22.

$$SHGC_i = \frac{SHGC_{g_i} \times A_{g_i} + SHCG_{f_i} \times A_{f_i}}{A_{pf_i}} \tag{4-22}$$

Where g and f denote properties of the glass and the frame, respectively.

The 2015 ASHARE Handbook provides tables to calculate $SHGC_g$ and $SHGC_f$ where the input is the window's glazing system, shading, and orientation. Therefore, $SHGC_g$ and $SHGC_f$ are functions of *BO, WT, WSH*, or as expressed by Equations 4-23a and 4-23b (See Figure 4-7 for *BO* explanation).

$$SHGC_{g_i} = g(BO, WT, WSH) \tag{4-23a}$$

$$SHCG_{f_i} = z(BO, WT, WSH) \tag{4-23b}$$

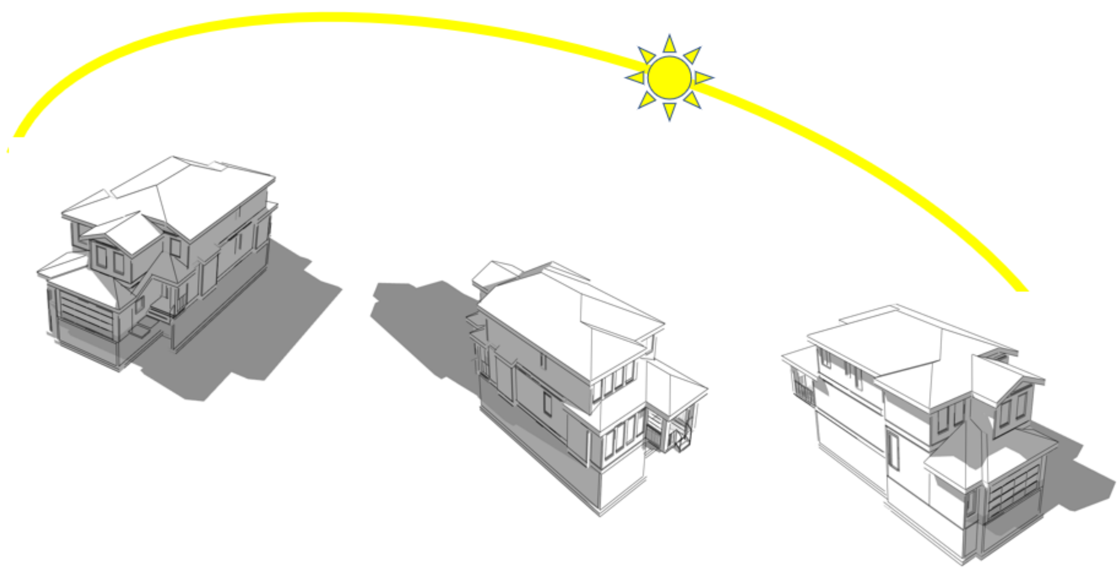


Figure 4-7 Explanation of building orientation

Based on Equations 4-19, 4-22, and 4-23, SHGC for a façade (i) is calculated as per Equation 4-24:

$$SHGC_i = \frac{g(BO, WT, WSH) \times \alpha \times A_{pf_i} + z(BO, WT, WSH) \times (1-\alpha) \times A_{pf_i}}{A_{pf_i}} \tag{4-24}$$

Note that A_{pf} is calculates as per Equation 4-20.

Given Equations 4-21 and 4-24, where A_{pf} is calculates as per Equation 4-20, Q_{fen} is assessed as per Equation 4-25.

$$
\begin{aligned}
&Q_{fen} \\
&= \sum_{i=1}^{4} \Big(\frac{f(WT) \times \alpha A_{pf_i} + U_{f_i} \times (1-\alpha) \times A_{pf_i}}{A_{pf_i}} \times A_{pf_i} \times (t_{out} - t_{in}) \\
&+ \left(\frac{g(BO, WT, WSH) \times \alpha \times A_{pf_i} + z(BO, WT, WSH) \times (1-\alpha) \times A_{pf_i}}{A_{pf_i}} \right) A_{pf_i} E_t \\
&+ (AL) A_{pf_i} \rho C_p (t_{out} - t_{in}) \Big)
\end{aligned}
\tag{4-25}
$$

The heat gain/loss from opaque area can be assessed as follows (Hutcheon and Handegord 1983):

$$
Q_{opa} = \textstyle\sum_{i=1}^{n} (t_{out} - t_{in}) \frac{AW_i}{TH_i \times RV_i} \tag{4-26}
$$

where AW_i, TH_i, and RV_i are the area, the thickness, and R-value of the opaque area, respectively. Note that the thickness of the exterior wall is related to the size of the used studs, and therefore to the construction material of the studs. Having said that, it is possible to write

$$
TH_i = p(CM_i) \tag{4-27}
$$

Then Equation 4-26 can be rearranged as follows:

$$
\begin{aligned}
Q_{opa} = (t_{out} - t_{in}) \frac{RCA}{TH_R \times RRV} \\
+ \sum_{i=1}^{n} (t_{out} - t_{in}) \frac{WA_i}{p(CM_{stud}) \times WRV}
\end{aligned}
\tag{4-28}
$$

where TH_R denotes the thickness of the exposed portion of the roof, and RCA refers to the area of the exposed portion of the roof.

Q_{fen} and Q_{opa} change due to the changes in the outdoor temperature, which implies fluctuation in the daily energy demand (Q). Thus, the largest value for Q accounts for the cooling demand, while the smallest accounts for heating demand. This demand should be offset by the heating/cooling generated by the HVAC systems. The energy demand, thus, is dependent of the following design variables: *BO*, *WWR*, *WT*, *WSH*, *WRV*, *RRV*, *CM*, (see Equations 4-25 and 4-28) and *HVAC*. The generated energy, then, can be given as follows:

$$
\begin{aligned}
GE &= \bigvee_{HVAC_i} \Bigg[Q_{int} \\
&+ \sum_{i=1}^{4} \Bigg(\frac{f(WT) \times \alpha A_{pf_i} + U_{f_i} \times (1-\alpha) \times A_{pf_i}}{A_{pf_i}} \times A_{pf_i} \times (t_{out} - t_{in}) \\
&+ \left(\frac{g(BO, WT, WSH) \times \alpha \times A_{pf_i} + z(BO, WT, WSH) \times (1-\alpha) \times A_{pf_i}}{A_{pf_i}} \right) A_{pf_i} E_t \\
&+ (AL) A_{pf_i} \rho C_p (t_{out} - t_{in}) \Bigg) + (t_{out} - t_{in}) \frac{RCA}{TH_R \times RRV} \\
&+ \sum_{i=1}^{n} (t_{out} - t_{in}) \frac{WA_i}{p(CM_{stud}) \times WRV} \Bigg]
\end{aligned}
\tag{4-29}
$$

$\bigvee_{HVAC_i} x$ denotes the generated energy by the HVAC system (*i*) to offset the heat gain/loss (*x*).

As can be seen, the manual process of calculating the heating and/or cooling load is extremely time consuming and requires quantifying many intermediate values. Therefore, energy analysis is usually performed using specialized software, such as Green Building Studio GSB®[5], which is the software used in this case study.

- The interactions between the design variables and operational cost:

The operational cost stems from three components: the cost of fuel consumed to generate the necessary energy, or C_{fuel}; the cost of electricity consumed to power existing systems and

[5] An energy analysis platform from Autodesk® that allows direct import from Revit®

equipment (e.g., lighting, HVAC, electrical appliances, etc.), or C_{elec}; and the cost of maintaining building components, or C_{maint}. Operational cost, therefore, can be calculated as follows:

$$C_{ops} = C_{fuel} + C_{elec} + C_{maint} \tag{4-30}$$

The present research uses the "failure model" to predict the behaviour of systems during operations, which assumes that systems do not undergo maintenance after failure. Hence, $C_{maint} = 0$. Equation 4-30, thus, can be reduced to Equation 4-31.

$$C_{ops} = C_{fuel} + C_{elec} \tag{4-31}$$

Based on Equation 4-29, it is possible to state the following:

Green Building Studio (GBS®) is used to perform the energy analysis for the original design in order to assess C_{fuel} and C_{elec}. The results indicate that the projected total operation cost will be CA$2,515.97 annually.

- The interactions between the design variables and operational energy:

Like the operational cost, the operational energy (EC_{ops}) is the sum of the energy consumed in the form of fuel (e.g., gas), or EC_{fuel}, and the equivalent energy amount to the consumed electricity, or EC_{elec}, as expressed in Equation 4-32.

$$EC_{ops} = EC_{fuel} + EC_{elec} \tag{4-32}$$

Note that: $EC_{ops} = GE_i = V_{HVAC_i}\Big[Q_{int} + \sum_{i=1}^{4}\big(\frac{f(WT)\times\alpha A_{pf_i} + U_{f_i}\times(1-\alpha)\times A_{pf_i}}{A_{pf_i}} \times A_{pf_i} \times (t_{out} - t_{in}) + \left(\frac{g(BO,WT,WSH)\times\alpha\times A_{pf_i} + z(BO,WT,WSH)\times(1-\alpha)\times A_{pf_i}}{A_{pf_i}}\right) A_{pf_i} E_t + (AL) A_{pf_i} \rho C_p (t_{out} - t_{in})\big) + (t_{out} - t_{in}) \times \frac{RCA}{TH_R \times RRV} + \sum_{i=1}^{n} (t_{out} - t_{in}) \times \frac{WA_i}{p(CM_{stud})\times WRV}\Big]$.

Based on the energy analysis performed for the case study house, the expected annual operational energy consumption is 47,007 MJ.

- The interactions between the design variables and emitted carbon:

CO_2 emissions during operation can also be understood as the combination of emissions due to fuel consumption (CeM_{fuel}) and to electricity consumption (CeM_{elec}). In fact, CeM_{elec} measures the emissions resulting from operations related to generation and supply of electricity, rather that the emissions due to consumption by the end user. Thus, emitted carbon (CeM_{ops}) can be expressed as Equation 4-33.

$$CeM_{ops} = CeM_{fuel} + CeM_{elec} \tag{4-33}$$

Depending on the energy analysis report for the building, the projected annual emissions of CO_2 is 6.61 t.

4. *Develop the aggregated functions of the assessment criteria*

The aggregated functions form the global boundaries of the selection problem, where the assessment criteria are linked with the design variables. The aggregated functions are formed by substituting the sub-components of the assessment criteria (i.e., C_{con}, C_{con}, EC_{emb}, EC_{ops}, CeM_{fp}, and CeM_{ops}) with the functions formulated as per the interactions between the design variables and sub-components of the assessment criteria.

Based on Equations 4-2, 4-6, and 4-31, the aggregated function of cost (C) can be expressed as,

$$\begin{aligned} C = {} & Q_{CM_{studs}} \times UP_{CM_{studs}} + Q_{CM_{joist}} \times UP_{CM_{joist}} + Q_{CM_{truss}} \times UP_{CM_{truss}} \\ & + \sum WWR_i \times WA_i \times UP_{WT} + UP_{WRV/SF} \times \sum FA_j + UP_{RRV/SF} \times RFA \\ & + C_{con_{HVAC}} + 275{,}740.49 + C_{fuel} + C_{elec} \end{aligned} \tag{4-34}$$

Based on Equations 4-3, 4-8, and 4-29, the aggregated function of energy consumption can be expressed as,

$$
\begin{aligned}
&EC \\
&= Q_{CM_{studs}} \times UEE_{CM_{studs}} + Q_{CM_{joist}} \times UEE_{CM_{joist}} + Q_{CM_{truss}} \times UEE_{CM_{truss}} \\
&+ \sum WWR_i \times WA_i \times UEE_{WT} + UEE_{WRV/SF} \times \sum FA_j + UEE_{RRV/SF} \times RFA \\
&+ \bigvee_{HVAC_i} \left[\sum_{i=1}^{4} \left(\frac{f(WT) \times \alpha A_{pf_i} + U_{f_i} \times (1-\alpha) \times A_{pf_i}}{A_{pf_i}} \times A_{pf_i} \times (t_{out} - t_{in}) \right. \right. \\
&+ \left(\frac{g(BO, WT, WSH) \times \alpha \times A_{pf_i} + z(BO, WT, WSH) \times (1-\alpha) \times A_{pf_i}}{A_{pf_i}} \right) A_{pf_i} E_t \\
&+ (AL) A_{pf_i} \rho C_p (t_{out} - t_{in}) \Big) + (t_{out} - t_{in}) \frac{RCA}{TH_R \times RRV} \\
&\left. + \sum_{i=1}^{n} (t_{out} - t_{in}) \frac{WA_i}{p(CM_{stud}) \times WRV} + Q_{int} \right] + EC_{emb_{HVAc}} + 1.3\text{x}10^6
\end{aligned}
\tag{4-35}
$$

Finally, the aggregated function for CO_2 emissions, based on Equations 4-4, 4-10, and 4-33, can be expressed as follows:

$$
\begin{aligned}
CeM = {} & Q_{CM_{studs}} \times UEC_{CM_{studs}} + Q_{CM_{joist}} \times UEC_{CM_{joist}} + Q_{CM_{truss}} \times UEC_{CM_{truss}} \\
& + \sum WWR_i \times WA_i \times UEC_{WT} + UEC_{WRV/SF} \times \sum FA_j \\
& + UEC_{RRV/SF} \times RFA + CeM_{ft_{HVAc}} + 70 + CeM_{feul} + CeM_{elec}
\end{aligned}
\tag{4-36}
$$

5. *Derive the aggregated functions according to each of the design variables*

The rationale in support of finding the derivatives of the aggregated functions is to study the effects of changes made to the design variables on the assessment criteria in order to reduce these impacts. Deriving the aggregated functions can be performed in two manners: (1) through direct analytical derivation, and (2) through conducting a sensitivity analysis for each design deliverable. The impact of design variables can be assessed by means of the following two assumptions:

(1) the collective change to the assessment criteria due to the changes in the design variable is assessed linearly; and

(2) the changes in design variable values are independent from one another.

The second assumption is important to allow the assessment of the change for each of the design variables to occur independently from the other, which is a necessary simplification herein due to the significant amount of manual calculations.

The process of evaluating the change caused in the assessment criteria by the design variable pertaining to the operational components is presented in Figure 4-8.

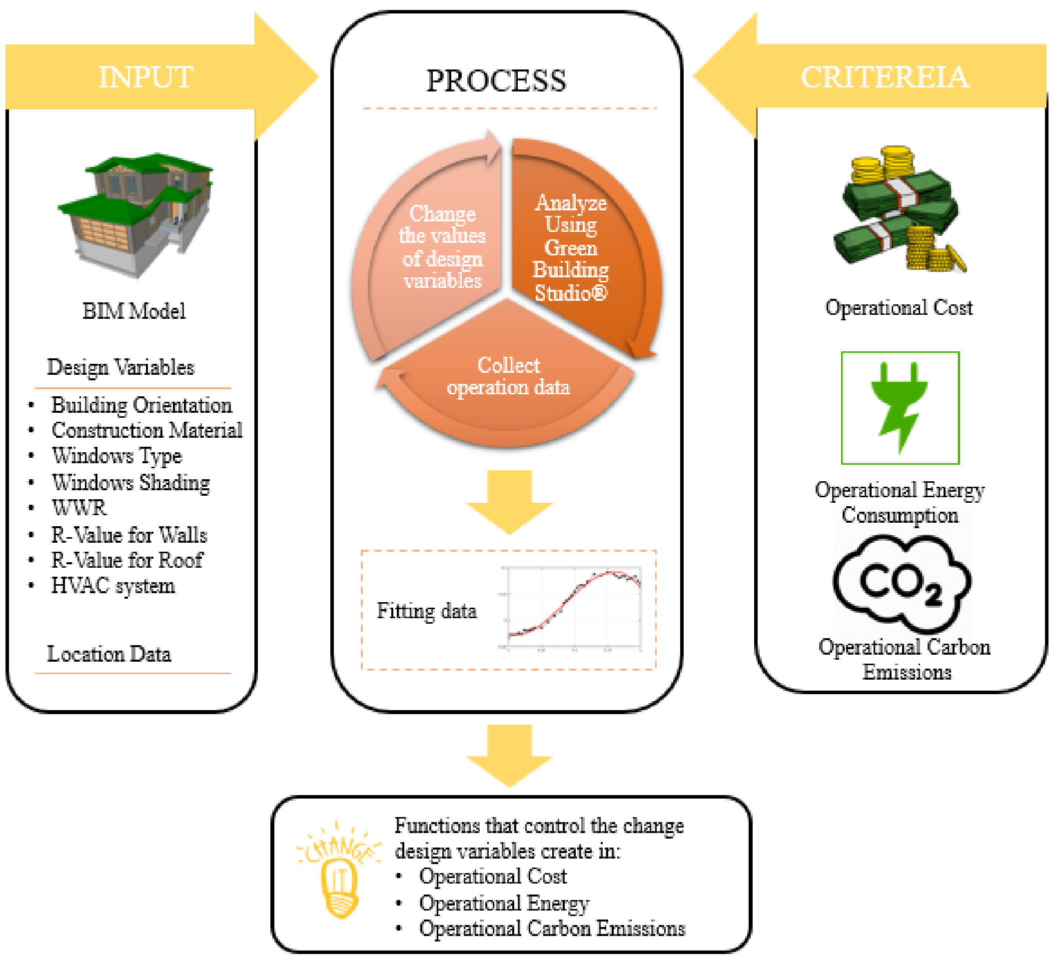


Figure 4-8 Process of assessing the change caused by design variables

This process involves the following steps:

1. Change the values of the design variable in the energy model in the GBS environment.
2. Run a comprehensive energy analysis using GBS each time the value of the design variable changes.
3. Collect operations-related criterion sub-components during each run and calculate the deviation from the original design.
4. Find the function that best fits the collected data.

Based on this information, the following discussion involves finding the derivative of the aggregated unions according to the design variables.

- **Cost aggregated function**

Changing the initial state of a small number design variable results in changes in construction cost. Also, a change in the initial state of a design variable (D_i) results in a change in it quantities of that variable of ΔQ_i and/or in its initial unit price of ΔUP_i. This leads to a change in the construction cost by ΔC_{con_i}. The total change in the construction cost due to the changes in all design variables can be expressed as Equation 4-36:

$$\Delta C_{con} = \sum_{i=}^{m} \Delta C_{con_i} \tag{4-36}$$

where m is the number of design variables.

However, in some cases ΔC_{con_i} is small, and therefore, can be ignored, because the changes it causes are marginal compared to the effort required to quantify them. Table 4-5 presents the effect of changing the design variables on C_{con}.

Table 4-5 Changes in construction cost due to changes in design variables

Design Variable	Change	ΔC_{con_i}
BO (initial state: 0°)	No change	0
CM (initial state: Wood)	Reduces the quantities needed while increasing the unit price	$\Delta Q_{CM} \times \Delta UP_{CM}$
WT (initial state: double-glazed)[1]	Increase of CA$5.78 for triple-glazed Decrease of CA$5.22 for single-glazed No change in the quantities	$Wall - Area \times Q_{WWR} \times \Delta UP_{WT}$
WSH	No change	0
WWR[1]	Changes the area of the glazes portion of the walls	$Wall - Area \times \Delta Q_{WWR} \times UP_{WT}$
WRV	Changes the quantities/quality of insulation materials	$\Delta UP_{WRV/SF} \times \sum FA_j$
RRV	Changes the quantities/quality of insulation materials	$\Delta UP_{RRV/SF} \times RFA$
HVAC	Assumed to have no change	0

[1] The change must be assessed for each façade.

Based on the linearity assumption, it is possible to write

$$\Delta C_{ops} = \Delta C_{feul} + \Delta C_{elec} = \sum_{i=1}^{m} \Delta C_{feul_i} + \sum_{i=1}^{m} \Delta C_{elec_i} \tag{4-37}$$

where ΔC_{ops} represents the total change in the operational cost; ΔC_{fuel_i} represents the change in the fuel cost due a change in design variable *i*; and ΔC_{elec_i} represents the change in the electricity cost due a change in design variable i.

- Beginning with building envelope design variables, to determine the equation governing the changes these variables create, this case study evaluates the effect of changing the WWR

of a certain façade for various combinations of window types and the amount to which they are shaded. Using the steps which were outlined at the beginning of this section for evaluating the changes during the operation phase, the impact of change on C_{ops} when windows on the *S-WWR* are double-glazed and are one-third shaded is as follows:

$$\Delta C_{ops_{S-WWR-1}} = 0.0003 * S-WWR^{3} - 0.076 * S-WWR^{2} - 0.452 * S-WWR + 7.41 \tag{4-38}$$

Figure 4-9 provides a graphical representation of the changes in C_{ops} due to changes in *S-WWR*. It should be noted that, similar to the conversion used while assessing the change of the construction related components, a positive change reflects a reduction in the value of the assessment criterion being studied.

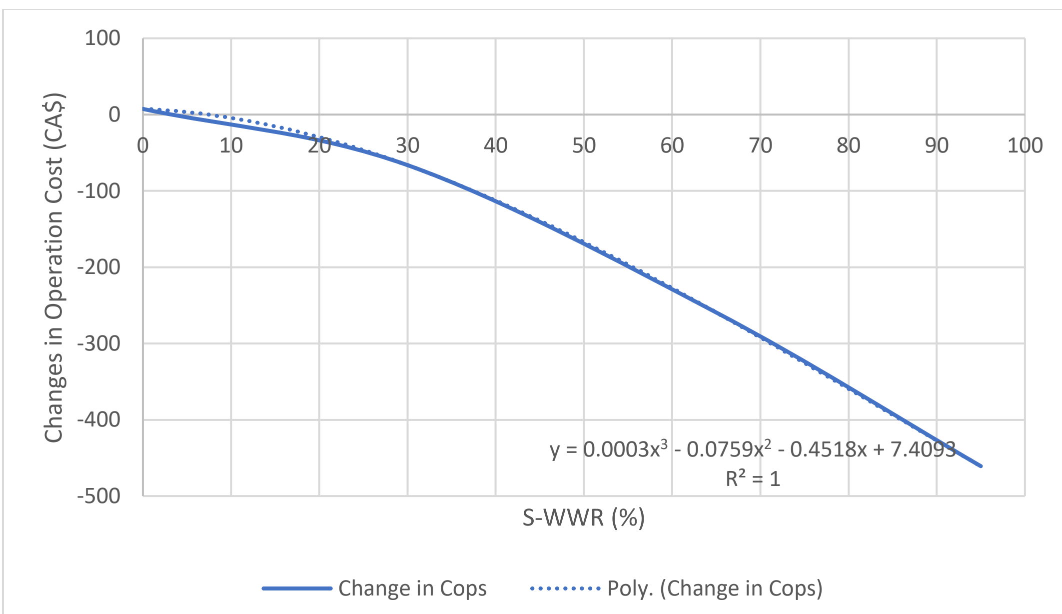


Figure 4-9 Changes in C_{ops} due to changes in *S-WWR*

The full set of equations pertaining to C_{ops} changes due to *WWR, SH,* and *WT* can be found in Appendix D.

- *OB* changes have the following impact on C_{ops}:

$$\Delta C_{ops_{OB}} = 4 \times 10^{-8} * OB^4 - 1 \times 10^{-5} * OB^3 + 0.0022 * OB^2 + 0.8332 * OB - 0.0476 \tag{4-39}$$

Figure 4-10 provides a graphical representation of the changes in the C_{ops}.

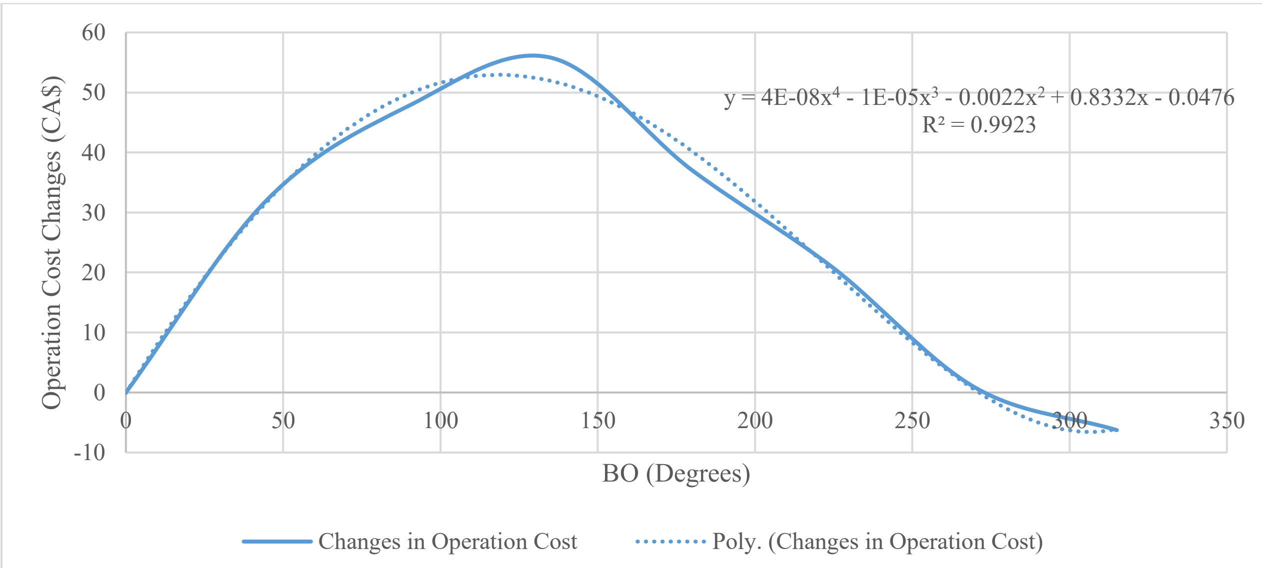


Figure 4-10 Changes in C_{ops} due to changes in *OB*

- *RRV* changes have the following impact on C_{ops}:

$$\Delta C_{ops_{RRV}} = -0.124 * RRV^3 + 12.1 * RRV^2 - 279.03 * RRV + 919.05 \tag{4-40}$$

- *WRV* changes have the following impact on C_{ops}:

$$\Delta C_{ops_{WRV}} = 0.65 * WRV^4 - 43.7 * WRV^2 + 996.35 * WRV - 7645.9 \tag{4-41}$$

- Impact due to changes in the construction material on the C_{ops} are to be considered as 0.
- Impact of HVAC system is presented in Table 4-6, where positive value reflects reduction in the annual cost.

Table 4-6 Operational cost changes due to HVAC change

System	Annual ΔC_{ops}
HVAC1	CA$184
HVAC2	CA$183
HVAC3	CA$892
HVAC4	CA$(183)
HVAC5	CA$(871)
HVAC6	CA$ (332)
HVAC7	CA$1,421

Therefore, the derivative of the cost aggregated function according to the deliverables is as follows:

- An example of the building envelope variables is the S-WWR when the windows are double-glazed and one-third shaded where the derivative reads:

$$\Delta C_{S-WWR-1} = 0.0003 * S - WWR^{3} - 0.076 * S - WWR^{2} - 0.452 * S - WWR + 7.41 + \Delta Q_{WWR} \times UP_{WT} \times WA_{S} \tag{4-41}$$

where WA_S represents the total area of wall in southern façade.

- *OB* changes have the following impact on *C:*

$$\Delta C_{OB} = 4 \times 10^{-8} * OB^{4} - 1 \times 10^{-5} * OB^{3} + 0.0022 * OB^{2} + 0.8332 * OB - 0.0476 + 0 \tag{4-42}$$

- *RRV* changes have the following impact on *C*:

$$\Delta C_{RRV} = -0.124 * RRV^{3} + 12.1 * RRV^{2} - 279.03 * RRV + 919.05 + \Delta UP_{RRV/SF} \times RFA \tag{4-43}$$

- *WRV* changes have the following impact on *C*:

$$\Delta C_{WRV} = 0.65 * WRV^{4} - 43.7 * WRV^{2} + 996.35 * WRV - 7645.9 + \Delta UP_{WRV/SF} \times \sum FA_{j} \tag{4-44}$$

- *CM* changes have the following impact on *C*:

$$\Delta C_{CM} = \Delta Q_{CM} \times \Delta UP_{CM} \tag{4-45}$$

- Impact of *HVAC* changes on *C* remains as presented in Table 4-6.

- **Energy Consumption aggregated function**

Similar to construction cost, changing the initial state of some design variables results in changes in the amount of embodied energy. Similarly, a change in the initial state of a design variable (D_i) results in a change in embodied energy by ΔEC_{emb_i}. Note that, as per the ICE database (Circular Ecology 2011) for assessing the environmental impact of material, glass has a small impact on the embodied energy compared to other materials used for construction (15 MJ/kg). Therefore, the impact of changes in variables related to windows will be ignored. Table 4-7 presents the effect of changing the design variables on EC_{emb}.

Table 4-7 Changes in embodied energy due to changes in design variables

Design Variable	Change	$\Delta \boldsymbol{EC_{emb}}$
BO (initial state: 0°)	No Change	0
CM (initial state: Wood)	Reduces the material consumption, but drastically increases the UEE_i when using steel	$\Delta QM_{CM} \times \Delta UE_{CM}$
WT	Ignored	0
WSH	Ignored	0
WWR	Ignored	0
WRV	Assumed to have no change	0
RRV	Assumed to have no change	0
HVAC	Assumed to have no change	0

The impacts of changes to the design variables on the operational energy is calculated in the same way as the impacts on the operational cost, i.e., fitting the data obtained from the energy analysis report, as follows:

- *OB* changes have the following impact on EC_{ops}:

$$\Delta EC_{ops_{OB}} = 4 \times 10^{-9} * OB^5 - 4 \times 10^{-6} * OB^4 + 0.0014 \times OB^3 - 0.23 * OB^2 + 17.6 * OB + 0.24 \tag{4-46}$$

Figure 4-11 graphically represents the changes in the EC_{ops} due to the changes in the values of *OB*.

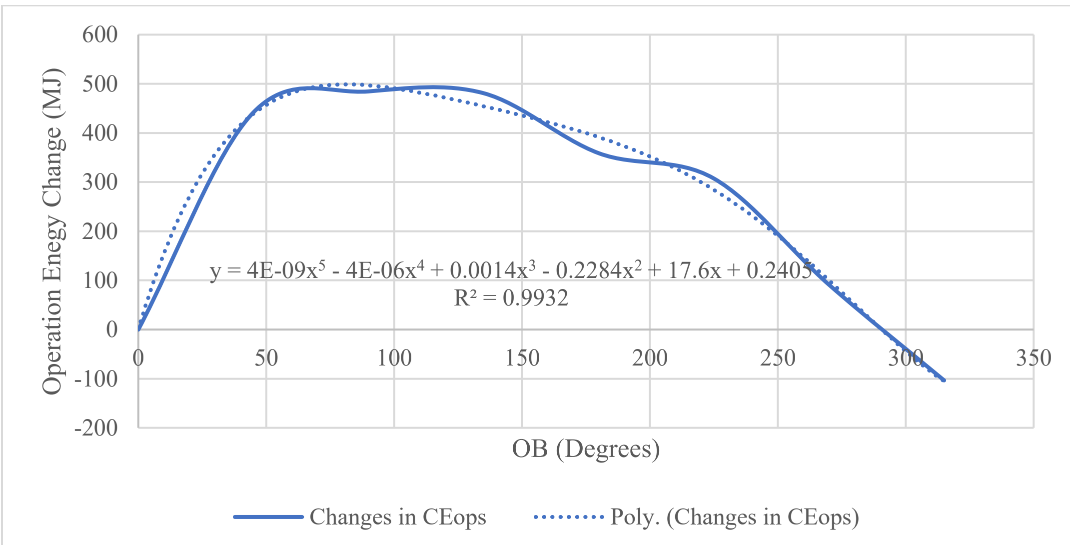


Figure 4-11 Changes in CE_{ops} due to changes in *OB*

- *RRV* changes have the following impact on EC_{ops}:

$$\Delta EC_{ops_{RRV}} = -8.131 * RRV^2 - 935.44 * RRV - 17516 \tag{4-47}$$

Figure 4-12 graphically represents the changes in EC_{ops} due to the changes in the values of *RVV*.

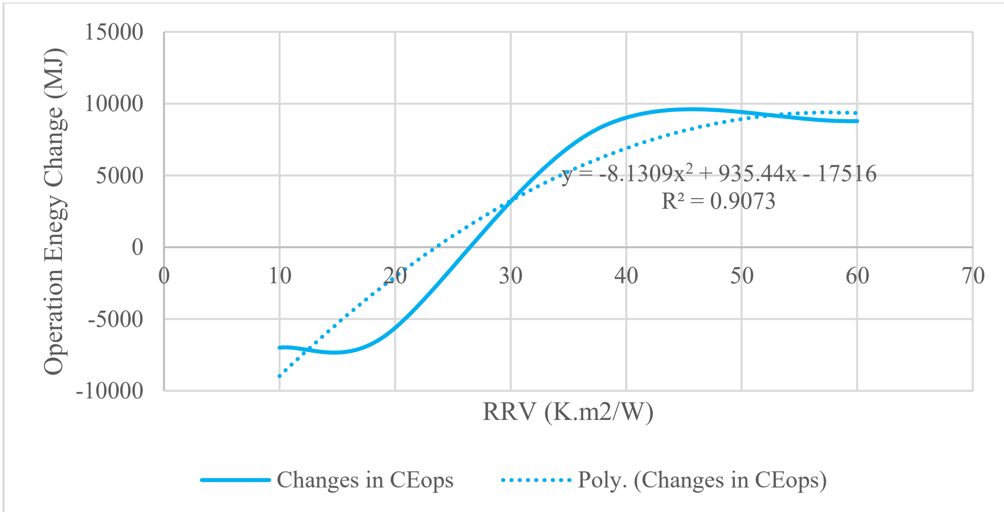


Figure 4-12 Changes in CE_{ops} due to changes in RRV

- WRV changes have the following impact on EC_{ops}:

$$\Delta EC_{ops_{WRV}} = -0.3502 * WRV^3 - 50.68 * WRV^2 + 2368.6 * WRV - 30172 \tag{4-48}$$

Figure 4-13 provides a graphical representation of the changes in the EC_{ops} due to the changes in the values of RVV.

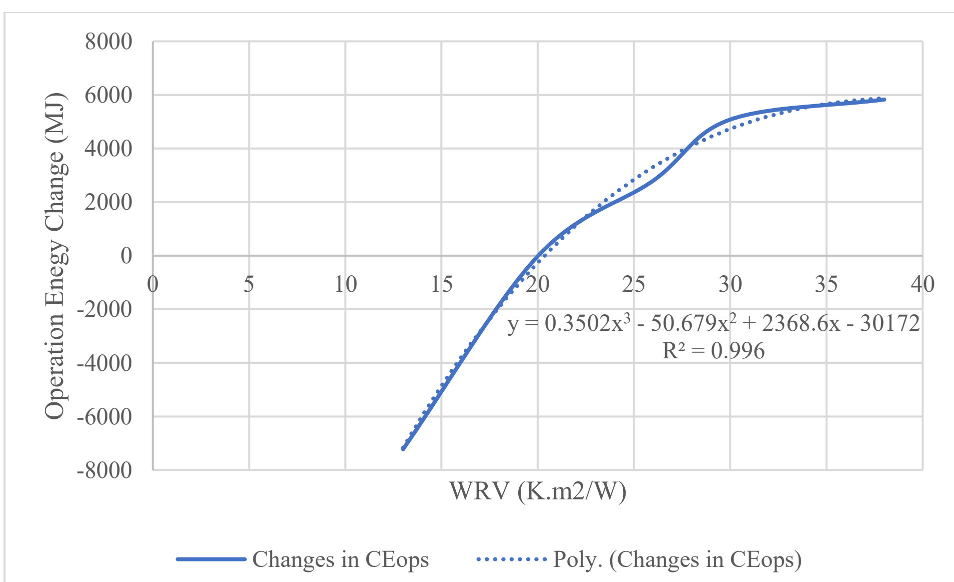


Figure 4-13 Changes in CE_{ops} due to changes in WRV

- *S-WWR* changes have the following impact on EC_{ops}:

In the case of double-glazed windows that are one-third shaded, while the full set of equations can be found in Appendix C,

$$\Delta EC_{ops_{S-WWR-1}} = 0.012 * S - WWR^2 - 3.165 * S - WWR^2 - 14.26 \times S - WWR + 9.86 \quad (4\text{-}49)$$

The full set of equations pertaining to CE_{ops} changes due to *WWR, SH,* and *WT* can be found in Appendix E.

Figure 4-14 graphically represents the changes in EC_{ops} due to the changes in the values of *S-WWR*.

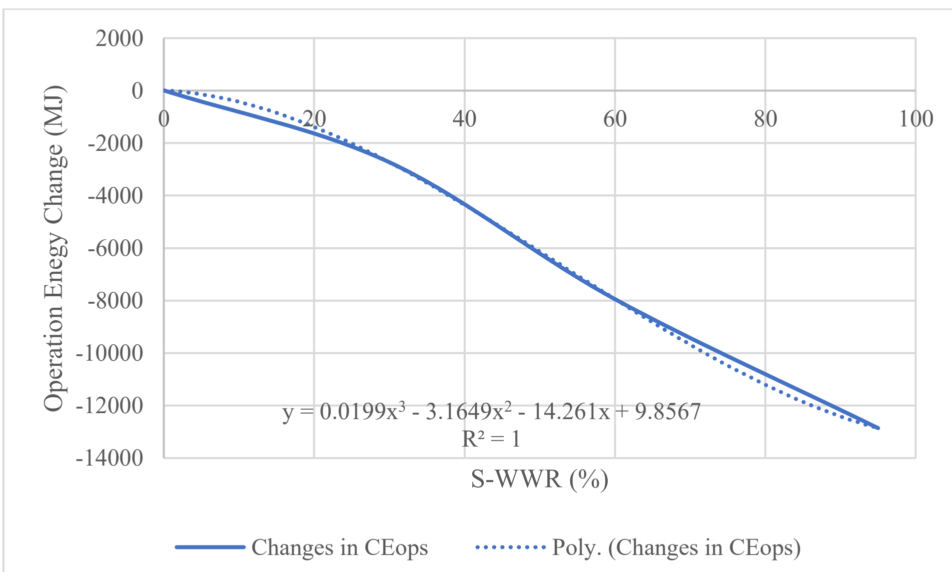


Figure 4-14 Changes in EC_{ops} due to changes in *S-WWR*

- Impact due to changes in the construction material on the EC_{ops} is 0.
- Impact of HVAC system is as presented in Tables 4-8, where positive value reflects reduction in the annual EC_{ops}.

Table 4-8 Changes in operational energy consumption due to changes in HVAC system

System	Annual ΔEC_{ops} (MJ)
HVAC1	−77,508
HVAC2	−77,271
HVAC3	8,255
HVAC4	−3,392
HVAC5	15,833
HVAC6	−93,733
HVAC7	26,028

The derivative of the energy aggregated function according to the deliverables is as follows:

- S-WWR when the windows are double-glazed and one-third shaded where the derivative reads:

$$\Delta EC_{S-WWR-1} = 0.012 * S - WWR^3 - 3.165 * S - WWR^2 - 14.26 \times S - WWR + 9.86 + 0 \quad (4\text{-}50)$$

- OB changes have the following impact on EC:

$$\Delta EC_{OB} = 4 \times 10^{-9} * OB^5 - 4 \times 10^{-6} * OB^4 + 0.0014 \times OB^3 - 0.23 * OB^2 + 17.6 * OB + 0.24 + 0 \quad (4\text{-}51)$$

- RRV changes have the following impact on EC:

$$\Delta EC_{RRV} = -8.131 * RRV^2 - 935.44 * RRV - 17516 + 0 \quad (4\text{-}52)$$

- WRV changes have the following impact on EC:

$$\Delta EC_{WRV} = -0.3502 * WRV^3 - 50.68 * WRV^2 + 2368.6 * WRV - 30172 + 0 \quad (4\text{-}53)$$

- CM changes have the following impact on EC:

$$\Delta EC_{CM} = \Delta QM_{CM} \times \Delta UE_{CM} \quad (4\text{-}54)$$

- $HVAC$ changes on EC remain as presented in Table 4-8.

- **CO_2 emissions aggregated function**

This occurs when a change in a design variable (D_i) results in a change in the embodied carbon by ΔCeM_{fp_i}. The embodied carbon in unit weight of glass is 0.86 kg_{CO2}/kg (Circular Ecology 2011), and, therefore, changing window-related variables is assumed not to cause any changes in the embodied carbon. Based on this assumption, Table 4-9 presents the effect of changing the design variables on EC_{emb}.

Table 4-9 Changes in design variables due to changes in embodied carbon

Design Variable	**Change**	$\boldsymbol{\Delta CeM_{fp}}$
BO (initial state: 0°)	No Change	0
CM (initial state: Wood)	Reduces the material consumption, but drastically increase the UEC_i when using steel	$\Delta QM_{CM} \times \Delta UEM_{CM}$
WT	Ignored	0
WSH	Ignored	0
WWR[1]	Ignored	0
WRV	Assumed to have no change	0
RRV	Assumed to have no change	0
HVAC	Assumed to have no change	0

Following the same process to study the impact of changes to the design variables on the annual amount of emitted CO_2 leads to the following:

- *OB* changes have the following impact on CeM_{ops}:

$$\Delta CeM_{ops_{OB}} = 5.68 \times 10^{-10} * OB^5 - 5.68 \times 10^{-7} * OB^4 + 0.0002 \times OB^3 - 0.033 * OB^2 + 2.5 * OB + 0.034 \quad (4\text{-}55)$$

- *RRV* changes have the following impact on CeM_{ops}:

$$\Delta CeM_{ops_{RRV}} = -1.15 * RRV^2 - 132.8 * RRV - 2487.27 \quad (4\text{-}56)$$

- *WRV* changes have the following impact on CeM_{ops}:

$$\Delta CeM_{ops_{WRV}} = -0.05 * WRV^3 - 7.2 * WRV^2 + 336.34 * WRV - 4284.42 \quad (4\text{-}57)$$

- *S-WWR* changes have the following impact on CeM_{ops}:

For a double-glazed window that is one-third shaded,

$$\Delta CeM_{ops_{S-WWR-1}} = 0.002 * S - WWR^3 - 0.45 * S - WWR^2 - 2.02 \times S - WWR + 1.4 \quad (4\text{-}58)$$

The full set of equations pertaining to CeM_{ops} changes due to *WWR, SH,* and *WT* can be obtained by multiplying the equations provided in Appendix E by 0.142 kg CO_2/MJ.

- Impact due to changes in the construction material on the EC_{ops} is 0.
- Impact of HVAC system is as presented in Table 4-10, where positive value reflects reduction in the annual CeM_{ops}.

Table 4-10 Changes in operational CO_2 emissions due to changes in HVAC system

System	Annual ΔEC_{ops} (t)
HVAC1	−10.9
HVAC2	−10.8
HVAC3	1.2
HVAC4	−0.5
HVAC5	2.2
HVAC6	−13.2
HVAC7	3.7

Note that the unit of measurement for ΔEC_{ops} in Equations 4-55 to 4-58 is kg.

The derivatives will, then, be as follows:

- S-WWR when windows are double-glazed and openings are one-third shaded (see Figure 4-15 for the explanation of window shading) where the derivative reads:

$$\Delta CeM_{S-WWR-1} = 0.002 * S - WWR^2 - 0.45 * S - WWR^2 - 2.02 \times S - WWR + 1.4 + 0 \qquad (4\text{-}59)$$

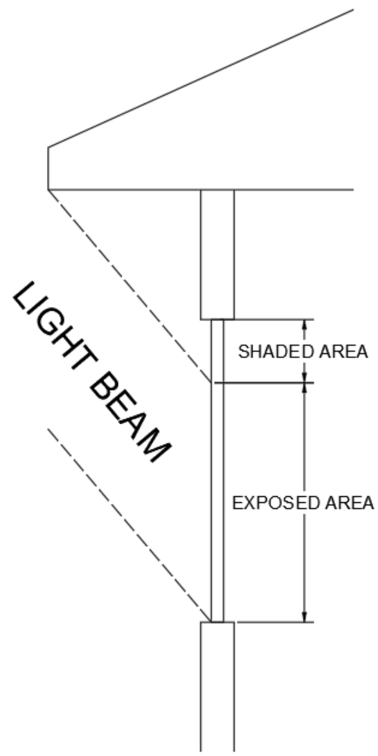


Figure 4-15 Shaded and exposed areas of window openings

- *OB* changes have the following impact on *CeM*:

$$\Delta CeM_{OB} = 5.68 \times 10^{-10} * OB^5 - 5.68 \times 10^{-7} * OB^4 + 0.0002 \times OB^3 - 0.033 * OB^2 + 2.5 * OB + 0.034 + 0 \qquad (4\text{-}60)$$

- *RRV* changes have the following impact on *CeM*:

$$\Delta CeM_{RRV} = -1.15 * RRV^2 - 132.8 * RRV - 2487.27 + 0 \qquad (4\text{-}61)$$

- *WRV* changes have the following impact on *CeM*:

$$\Delta EC_{WRV} = -0.05 * WRV^3 - 7.2 * WRV^2 + 336.34 * WRV - 4284.42 + 0 \quad (4\text{-}62)$$

- *CM* changes have the following impact on *CeM*:

$$\Delta EC_{CM} = \Delta QM_{CM} * \Delta UEM_{CM} \quad (4\text{-}63)$$

- Impact of *HVAC* changes on *CeM* remains as presented in Table 4-10.

6. *Define the technical performance measure to use and assess the design variables against one another*

Among the selected design variables, the HVAC system features a dynamic behaviour (i.e., functions in cycles of working and resting depending on the external conditions). Therefore, it is important to understand how the selection of design value will affect this behaviour. As mentioned earlier, the duty of the HVAC system is to offset the energy demand, and therefore, any design variable that affects the energy demand will affect the performance of the HVAC system.

As the model used to study the projected technical performance of systems is the failure model, the performance measure to be used is the mean time to failure (MTTF). Due to the lack of statistical information pertaining to the alternatives of the HVAC system, this case study will assign a survivor function ($R_i(t)$) for alternative i in order to assess the potential technical performance through calculating $MTTF_i$ that will measure the total amount of energy the system will generate before failure. Note that the number of years (yr_i) system i survives is assessed as per Equation 4-64.

$$yr_i = \frac{MTTF_i}{Annual\ Energy\ Demand} \quad (4\text{-}64)$$

Table 4-11 presents the given survivor function for each of the HVAC alternatives.

Table 4-11 *R(t)* and *MTTF* for the HVAC alternatives

System	$R_i(t)$	$MTTFi = \int_0^\infty Ri(t).dt$ (MJ)
HVAC1	$\frac{1 \times 10^7}{(t+6)^2}$	1,666,666.67
HVAC2	$1 \times 10^4(t^3 e^{-t})t$	240,000.00
HVAC3	$1 \times 10^7(e^{-0.2t})$	5,000,000.00
HVAC4	$\frac{1 \times 10^5}{(0.5t+0.2)^3}$	2,500,000.00
HVAC5	$1 \times 10^6(te^{-t^2})$	500,000.00
HVAC6	$1 \times 10^5(t^3 e^{-t})t$	2,400,000.00
HVAC7	$\frac{1 \times 10^7}{(t+6)^2}$	1,666,666.67

Based on the annual energy demand of the original design, Equation 4-63, Table 4-8 and Table 4-12 present the expected time to failure for each of the alternatives.

Table 4-12 Time to failure for each HVAC alternative based on the original design

System	$MTTFi = \int_0^\infty Ri(t).dt$ (MJ)	Time to Failure (years)
HVAC1	1,666,666.67	35.5
HVAC2	2,400,000.00	51.0
HVAC3	5,000,000.00	105.0
HVAC4	2,500,000.00	53.0
HVAC5	500,000.00	10.6
HVAC6	2,400,000.00	51.0
HVAC7	1,666,666.67	35.0

Note that as some systems may remain in service longer than others, they cause the annual energy consumption to increase. For example, HVAC1 has a relatively high expected lifespan, but when using this system, the annual energy demand will increase by 77,508 MJ, which leads to reducing its life span to 21.5 years. Therefore, the selection should not be based solely on performance. Hence, the next step.

7. *For each design variable find the alternative that best fits the correspondent derived functions and satisfies performance measure.*

In this step, the performance measures chosen and calculated in Step 6, with the aggregated function derivatives formulated in Step 5, are used to select the fittest alternatives for each design variable. Selection of the fittest alternative can be performed in one of two ways:

- multi-objective optimization, where the problem becomes finding the near optimum solution for a set of equations, or,
- trial-and-error, where values of the design variables are changed, assessed, and then ranked. Then he alternative of the highest rank is selected.

This section will outline the use of both approaches.

- Using the multi-objective optimization approach

To explain how to perform the selection following the multi-objective optimization approach, this section will use *OB* as an example, and will then show the selected alternatives for all other design variables.

The derivatives of the aggregated functions according to *OB* are as follows (as per Step 5, and Equations 4-42, 4-55, and 4-60):

$$\Delta C_{OB} = 4 \times 10^{-8} * OB^4 - 1 \times 10^{-5} * OB^3 + 0.0022 * OB^2 + 0.8332 * OB - 0.0476$$

$$\Delta EC_{OB} = 4 \times 10^{-9} * OB^5 - 4 \times 10^{-6} * OB^4 + 0.0014 \times OB^3 - 0.23 * OB^2 + 17.6 * OB + 0.24$$

$$\Delta CeM_{ops_{OB}} = 5.68 \times 10^{-10} * OB^5 - 5.68 \times 10^{-7} * OB^4 + 0.0002 \times OB^3 - 0.033 * OB^2 + 2.5 * OB + 0.034$$

The left-hand values of these equations have to be maximized, as well as the time to failure of the HVAC alternatives. Note that, as per Equation 4-64, the energy demand should be minimized, and therefore, maximizing the change in the energy demand is assigned the highest priority. Using generic algorithm to maximize the left-hand side of the equation leads to $OB = 45^o$.

Following a similar approach for the remaining variables, the proposed values for the design variables are presented in Table 4-13.

Table 4-13 Design variable values

Variable	Design Value	Proposed value
N-WWR	0.037	0.017
W-WWR	0.276	0.290
E-WWR	0.117	0.110
S-WWR	0.017	0.040
WSH	Windows' shading to remain as per design	
N-WT	Double glazed	Double glazed
W-WT	Double glazed	Double glazed
E-WT	Double glazed	Double glazed
S-WT	Double glazed	Double glazed
Building Orientation	0	45°
HVAC	ASHRAE Package System	High Eff. Package Terminal AC
Roof R-Value (K. m²/W)	35	46
Wall R-Value (K. m²/W)	24	38
Construction Material	Wood	Wood

Table 4-14 presents a comparison between the impact of the original design on values and the impact after the improvement. In the table, S1 indicates the original design, while S2 refers to the design after improvements.

Table 4-14 Comparison between the impact of original and recommended design

	Cost (CA$)				Carbon Emission (t)				Energy Consumption (MJ)			
	Construction Cost		Operation Cost (Annual)		Embodied Carbon		Emitted Carbon (Annual)		Embodied Energy		Consumed Energy (Annual)	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
	443,617	456,074	4,146	2,239	98	98	6.61	2.22	1.82×10^6	1.82×10^6	47,007	35,255
Difference (S1-S2)	−12,457 (2.8% increase)		1,907 (46% decrease)		0		4.39 (66% decrease)		0		11,752 (25% decrease)	

As can be noted, using the values proposed by the framework leads to an approximate 3% increase in the construction cost. However, further analysis reveals that the implementation of the proposed framework will save 46% of the operation cost, which indicates that the owner will significantly save over the life span of the house. There is no change in the embodied carbon or embodied energy since the construction material and building operation are not required to be changed. However, the maximum change is in the amount of emitted carbon, which undergoes a 66% decrease compared to the original design. Consumed energy presents the least improvement at 25%, which is still a considerable improvement compared to the amount of consumed energy due to the original design.

- Using multi-criteria utility function (MCUF)

The use of MCUF to evaluate the various design combinations requires assessing the utility of each of the proposed solutions, and since there are three criteria then the final utility is the weighted sum for the utilities of each of the assessed criteria as suggested by Georgy et. al (2005). The utility function that will be used in the present research is expressed as Equation 4-64.

$$U_j(s_i) = \frac{C_{o\,j}}{C_{o\,j} + C_{s_i\,j}} \tag{4-64}$$

where

$U_j(s_i)$ represents the criterion *j* utility of design scenario s_i,

$C_{o\,j}$ represents the value of criterion *j* as per the original design; and,

$C_{s_i\,j}$ represents the value of criterion *j* when using the design changes proposed in design scenario s_i.

Note that $0 \leq U_j(s_i) \leq 1$, where the higher the utility, the more desirable the design option. For example, measuring the utility of operation cost of RRV or $U_{C_{ops}}(RRV)$ leads to the graph presented in Figure 4-16.

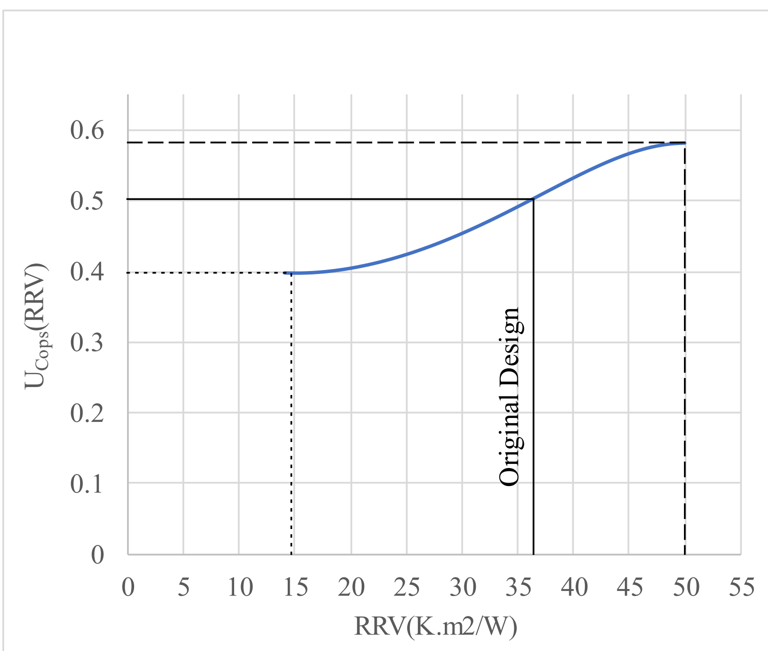


Figure 4-16 $U_{C_{ops}}(RRV)$

The graph depicts that the $U_{C_{ops}}(RRV)$ increases as RRV increase, which can be attributed to the fact that increasing RRV reduces the energy demand and, therefore, decreases C_{ops}. Since utility measures the preference of decision makers, and clearly the less cost the better, then the utility increases as RRV increases. It is also notable that $U_{C_{ops}}(RRV)$ is more sensitive to the changes of RRV within the interval [35, 50] compared to changes within [15, 35], which indicates that changes in the former interval are more effective and preferable.

For MCUF, the total utility of a design alternative is expressed as Equation 4-65 (Georgy et al. 2005).

$$U(s_i) = \sum_{j=1}^{n} w_j \times U(s_i)_j \tag{4-65}$$

where n represents the number of assessment criteria and w_j refers to the weight of each of the assessment criteria. Note that $\sum_{j=1}^{n} w_j = 1$.

In the present research, there are three assessment criteria, i.e., cost, energy consumption, and CO_2 emissions, which are evaluated over the lifecycle of the house. Each of these criteria encompasses a sub-component. Therefore, another weighting factor (wc_{ij}) is introduced to account for the relative importance of one sub-component to another; thus, wc_{ij} refers to the weight of component i of criterion j. As with w_j, $\sum_{i=1}^{n} wc_{ij} = 1$.

For the purpose of calculating the total utility for design scenarios, the following values for the weight factors apply: $wj = 1/3$ and $wc_{ij} = 0.5$.

To demonstrate the use of MCUF in this framework, the design scenarios that will be assessed are presented in Table 4-15.

Table 4-15 Design scenario definitions

Design Alternative	Definition
S1	The original design
S2	Using R-value of 36 for the roof and R-value of 26 for walls
S3	Using steel studs for the walls
S4	Using ASHRAE VAV package for HVAC
S5	Using changes explained in Table 4-13
S6	Rotating the building 90° counter-clockwise

To illustrate the calculations of the utility of sub-components for each of the design scenarios, the operation cost utility for each of the design scenarios ($U_{C_{ops}}(S_I)$) will be calculated. As per Equation 4-46, the C_{ops} utility of a design scenario (S_i) can be written as:

$$U_{C_{ops}}(s_i) = \frac{C_{o_{C_{ops}}}}{C_{o_{C_{ops}}} + C_{s_{i_{C_{ops}}}}} \tag{4-66}$$

Table 4-16 presents the results of this operation.

Table 4-16 C_{ops} utility of design scenarios

Scenario	**Operation Cost (CA$/yr)**	**Utility**
S1	4,146	0.5000
S2	3,951	0.5120
S3	4,146	0.5000
S4	5,510	0.4294
S5	2,233	0.6499
S6	3,995	0.5093

Figure 4-17, on the other hand, presents the distribution of the design scenarios on a utility function graph.

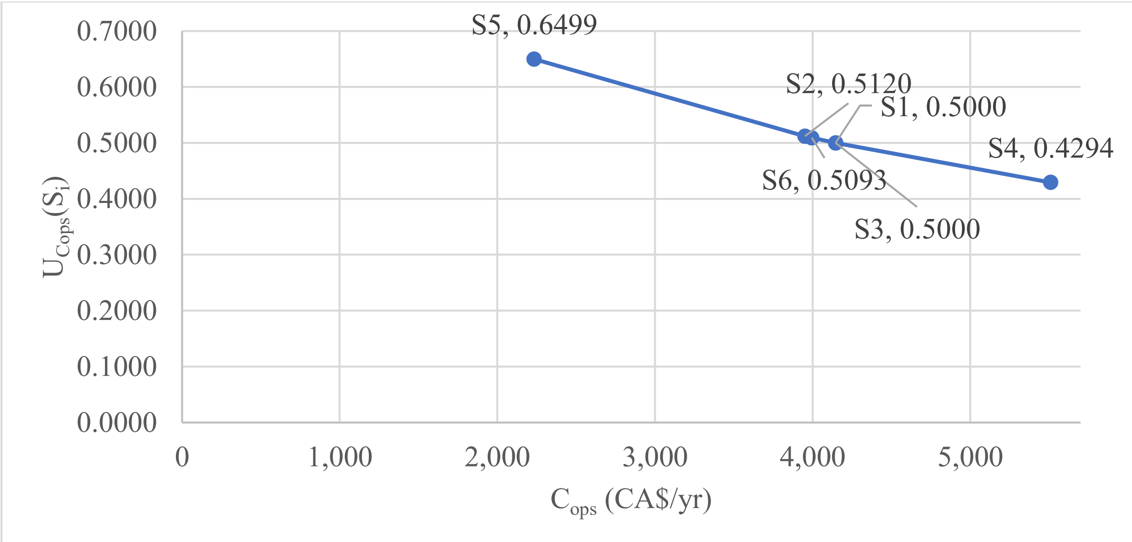


Figure 4-17 U_{Cops} for the considered scenarios

Based on Equations 4-2, 4-3, and 4-4, Equation 4-65 can be written as follows.

$$U(s_i) = \frac{(0.5*U_{Ccon}(s_i)+0.5*U_{Cops}(s_i)}{3} + \frac{(0.5*U_{CEcon}(s_i)+0.5*U_{CEops}(s_i)}{3} + \frac{(0.5*U_{CeMcon}(s_i)+0.5*U_{CeMops}(s_i)}{3} \tag{4-67}$$

Table 4-17 presents the corresponding total utility of design scenarios, calculated as per Equation 4-67.

Table 4-17 Design scenarios and their rankings

Scenario	Cost (CAD)		Carbon Emission (Metric tons)		Energy Consumption (MJ)		Total Utility
	Construction Cost	Operation Cost (Annual)	Embodied Carbon	Emitted Carbon (Annual)	Embodied Energy	Consumed Energy (Annual)	
S1	443,617	4,146	98	6.61	1.82×10^6	47,008.00	0.500
S2	450,754	3,951	98	6.24	1.82×10^6	46,108.04	0.505
S3	465,249	4,146	112	6.61	2.08×10^6	47,007.00	0.487
S4	450,249	5,510	98	9.12	1.82×10^6	59,778.59	0.464
S5	456,074	2,233	98	2.22	1.82×10^6	35,031.52	0.577
S6	443617	3,995	98	6.25	1.82×10^6	46,283.92	0.505

Figure 4-18 compares the various alternatives. Note that the closer the alternative is to the center of the diagram the better the alternative.

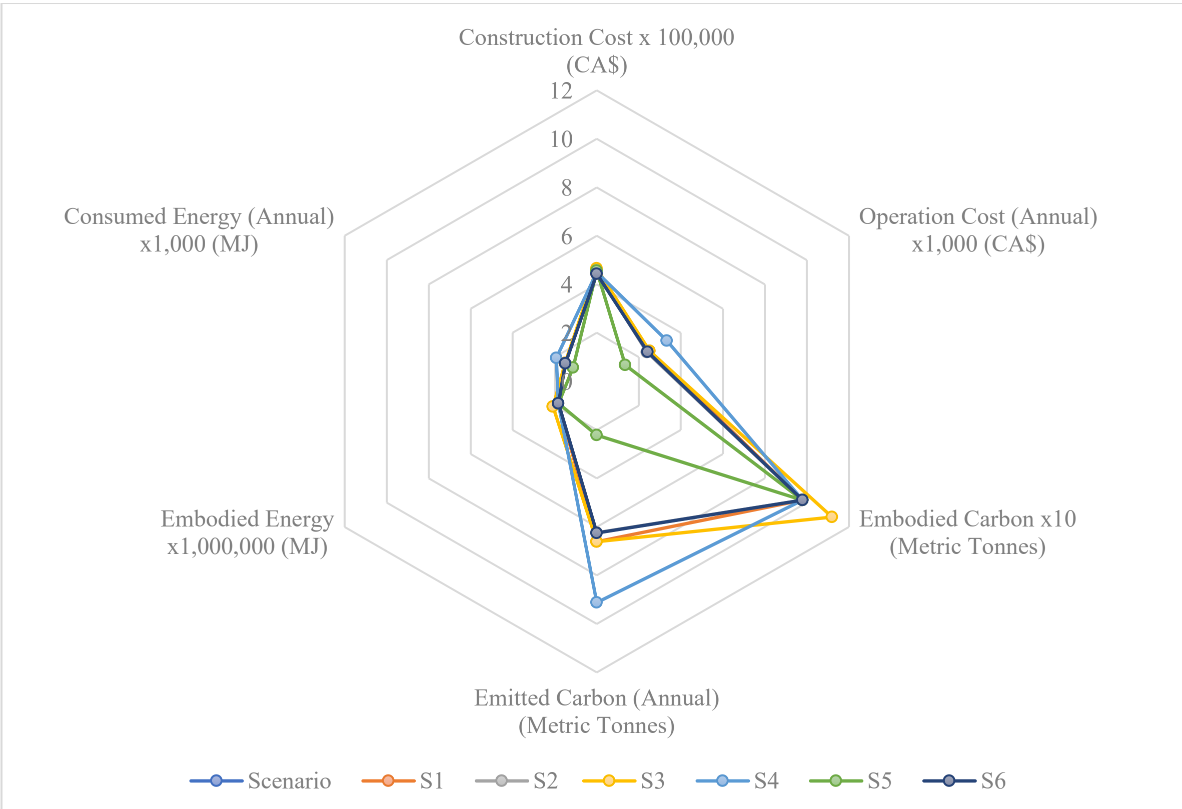


Figure 4-18 Comparison of the impact of the studied alternatives

Note that the total utility of S6 is the highest, which makes it the most preferable scenario that satisfies the stakeholder requirements of having lower financial and economic impact, and, given that it requires less energy to be produced, it leads to longer life expectancy of the HVAC systems.

4.2. Case Study 2: the application of the Multi-criteria Lifecycle Assessment design framework in a walk-up building

4.2.1 Introduction

As can be seen in Section 4.1, assessing the energy consumed during the operation of a building, and as a result, assessing the cost and CO_2 emissions associated with the amount of generated energy, is time consuming and requires extensive effort to solve all the relevant equations (Equations 4-15 to 4-29) every time a change occurs. In Section 4.1, GBS® is used to perform this analysis. However, although GBS® allows for the direct input of building parameters from BIM models, it uses a black box for energy analysis that the user has no control over, which limits the effort to automate the assessment of interactions between design variables and HVAC systems. EnergyPlus™, on the other hand, is a very powerful, widely used open-source energy analysis software that overcomes the transparency issues that exist in GBS®. However, due to the level of accuracy the EnergyPlus™ analysis provides, it requires a significant amount of input that may not be available at early design phases. Also, EnergyPlus™ requires a considerable amount of knowledge in energy analysis to be able to perform a reliable analysis using the software, which also may not be available during the design assessment.

The discussion from the previous section leads to the following points that need to be addressed in order to improve the outcomes and applicability of the MCLCA:

- transparent analysis engine that allows for customizability;
- simplified graphical user interface (GUI) for easy user interaction that does not jeopardize the accuracy of the results; and,
- account for the interdependencies that are related to energy demand.

These three points underscore the research motivation to undertake the development of an MCLCA energy analysis engine in the BIM environment to allow for the direct assessment of the interaction between (1) the design variables and the assessment criteria sub-components (i.e., operational cost, operational energy, and emitted carbon), and (2) between the design variables and considered building systems (i.e., heating system and lighting system in this case study).

4.2.2 The MCLCA energy analysis engine

The engine uses the heat balance method (HBM) that is described in Chapters 18 and 19 of ASHRAE (2013). This method depends less on assumption and offers more flexibility while maintaining accuracy (ASHRAE 2013). Additionally, HBM is suitable for a wide range of building types from single-family units to commercial and industrial buildings (ASHRAE 2013). Figure 4-19 presents the general zone HBM uses to assess energy demand. HBM assesses the heat exchanges between the surfaces confining the zones and the surrounding environment. Each of these surfaces has two distinct areas, opaque and fenestrated, which comprise 12 different surfaces through which heat can be exchanged. As per HBM, the total heat loads the system must provide to a zone (*j*) can be calculated as follows (ASHRAE 2013):

$$q_{sys_j} = \sum_{i=1}^{12} A_i h_{ci} \left(T_{si_{t,j}} - T_{a_j} \right) + q_{CE} + q_{IV} \tag{4-68}$$

where

- q_{sys_j} represents the heat transferred from the HVAC system to zone j;
- q_{CE} refers to the internal heat gain;
- q_{IV} represents heat load resulting from ventilation and infiltration;
- A_i indicates the area of surface i confining zone j;

- h_{ci} represents the indoor convective heat transfer coefficient;
- $T_{si_{t,j}}$ refers to the temperature of the external side of surface *i* of zone *j* at time step *t*; and,
- T_{a_j} represents the internal temperature of zone *j*.

Providing the detailed calculations pertaining to the application of Equation 4-68 is outside the scope of this thesis; the detailed explanation can be found in the ASHRAE Handbook 2013 as follows:

- evaluating q_{CE} and q_{IV} can be found in Chapters 14, 15, and 18; and
- assessing $T_{si_{t,j}}$ can be performed through equations detailed in Chapter 18.

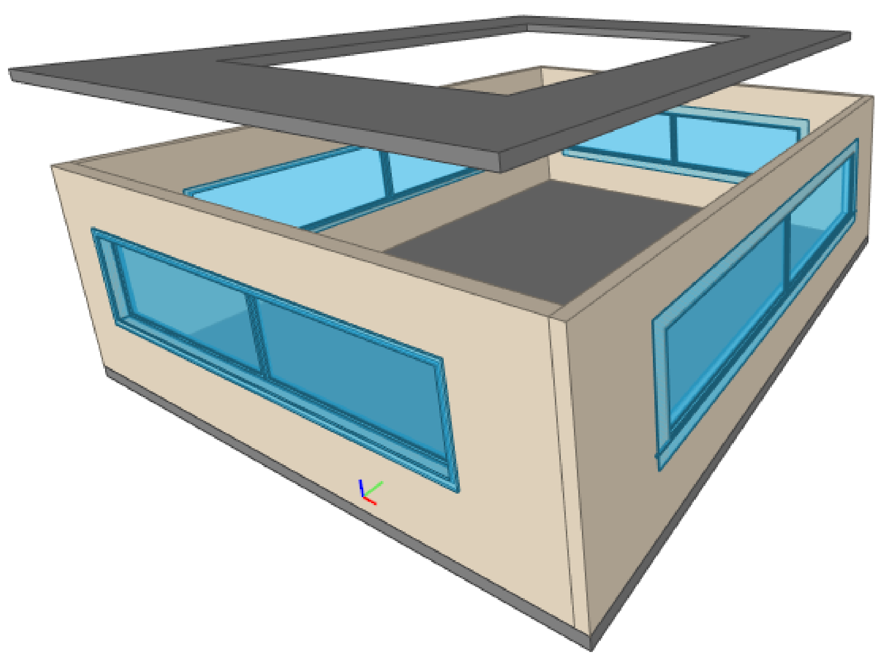


Figure 4-19 General conditioned zone as per HBM

Heating loads must be assessed for all the zones in the building, and the final sum of all the heating/cooling loads of all the zones is equal to the energy demand. The energy demand is then adjusted to account for the losses in the secondary systems (i.e., heat/load transferring system between the heating/cooling sources and heated/cooled zones such as ducts and fans) and primary systems (i.e., heating/cooling sources such a boilers). Losses in the primary and secondary systems is a function of the systems used and the conditions of operations. Chapter 19 of the ASHRAE Handbook elaborates in more detail on how to assess these losses.

The information flow in the developed engine is presented in Figure 4-20.

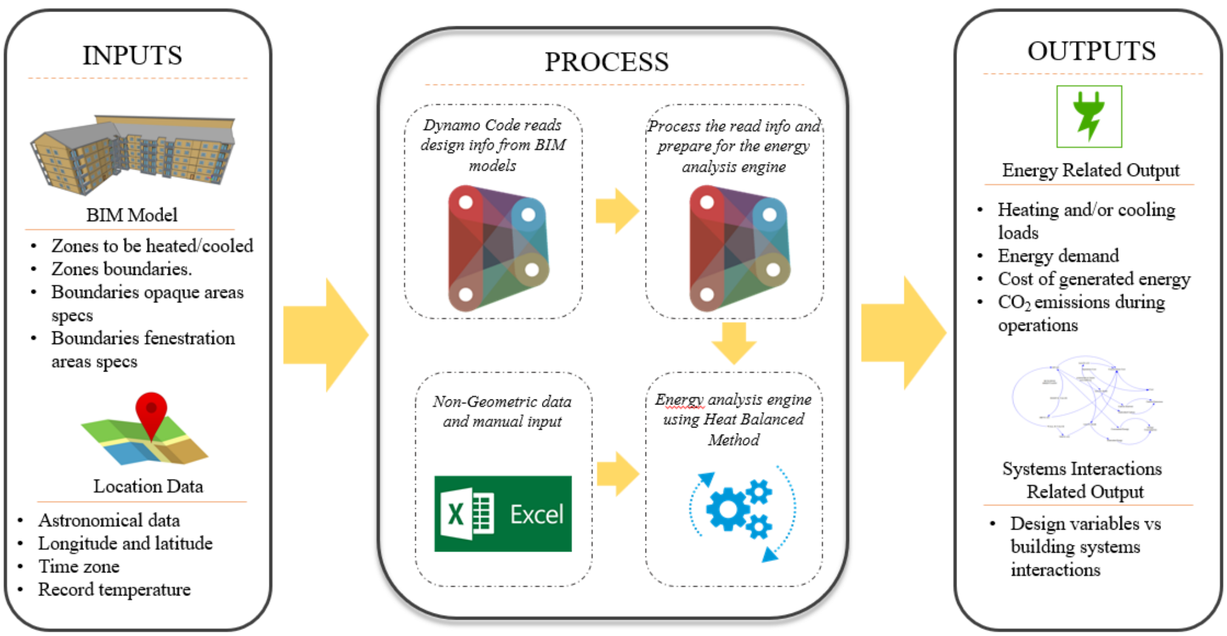


Figure 4-20 Information flow in the developed energy analyse engine

The geometrical information pertaining to the zones that need to be analyzed is stored in the BIM model, which may also contain information about thermal properties of the zone boundary. However, the method by which the information is stored requires further preparation to be readable by the energy analysis engine. Various modelling practices may affect the preparation process, which increases the manual work required prior to the energy analysis. Therefore, a routine is developed in the Dynamo environment (a graphical programming tool for Revit® that allows for processing of information stored in the BIM model) to read the information from the BIM model, prepare it as per the requirement of the energy analysis engine, and write it in the designated place for the geometric information. Figure 4-21 presents the developed Dynamo routine.

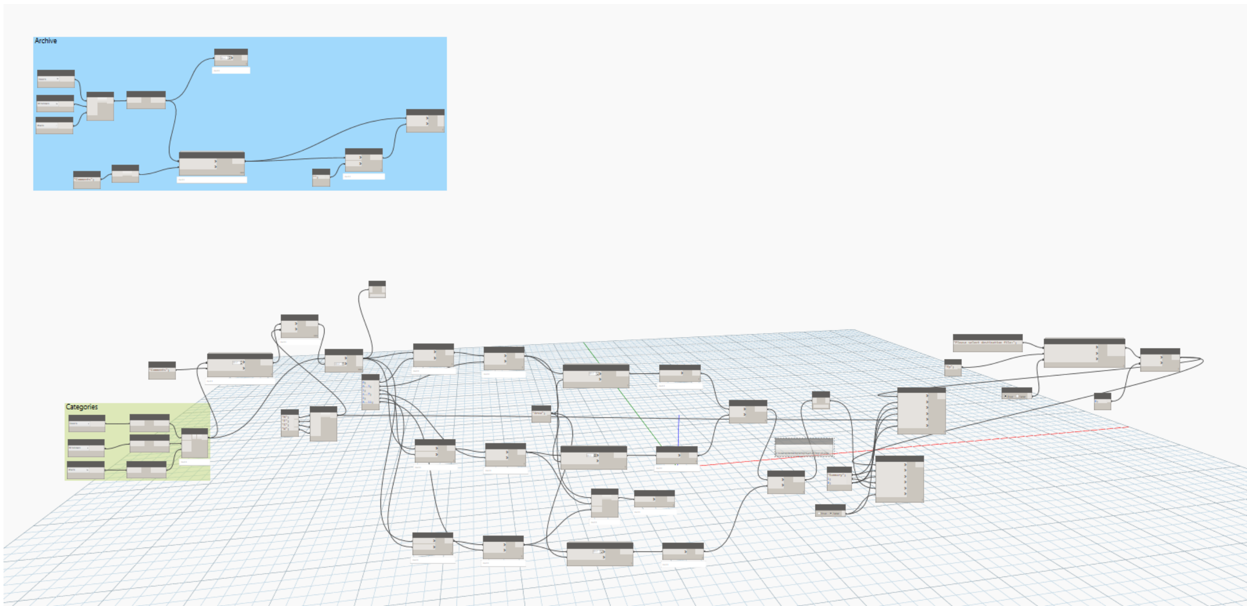


Figure 4-21 Developed Dynamo routine

Energy analysis also requires climate information related to the geographical location of the building. This information is fed into the model through spreadsheets. Spreadsheets are also used to input information pertaining to the zone bounding surfaces since the BIM model may not have all the required information (e.g., reducing the modelling effort required to develop the building model implies that some information, such as U-value, cannot be a necessary input into the model). Also, spreadsheets are used to quickly input additional parameters when the user is interested in assessing the impact of changing certain design parameters without the need to modify them in the BIM models, such as exploring different R-values for the building envelope.

Using the weather data, location information, geometrical data, and physical properties of the building components, the energy analysis engine calculates the heat loads and assesses the energy demands and potential energy consumption and visualizes this information.

As presented in Figure 4-21, the engine assists the user in evaluating the impact of design variables on the systems performance. To explain this aspect, Figure 4-22 presents the detailed use of Equation 4-68 in the assessment of the interactions between the components of the systems in a building. The heat load determines how much energy the heating system must generate to achieve a thermal comfort in the occupied zones. Heat load is affected by the heat exchange through the zone boundaries, which are determined by the geometrical and thermal properties of these surfaces, which belong to the building envelope. Heat load is also affected by the internal heat gain, which is influence by the appliances.

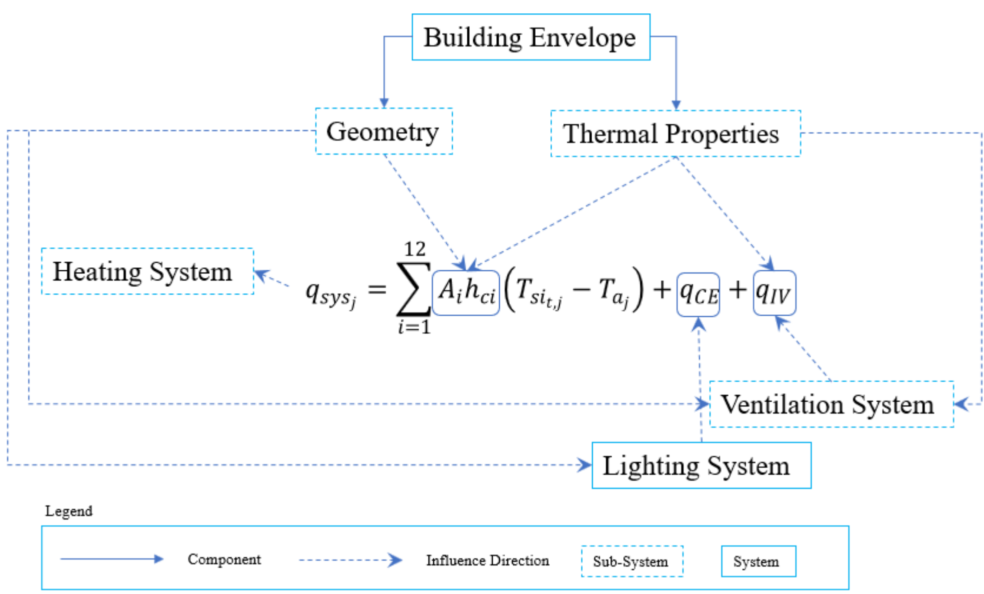


Figure 4-22 Interactions of systems in a building

The geometry of the building envelope also affects the lighting system, as more fenestration area leads to less artificial lightings. Building geometry also affects the ventilation system as the larger the zone is, the more air for ventilation is required. Ventilation systems are also affected by the thermal properties of the building envelope, especially air tightness. Therefore, changes to any of the properties of building envelope, ventilation system, and lighting system will affect the heating system. The developed engine can quantify the magnitude of these changes and the sensitivity of the considered systems toward these changes.

The developed energy analysis engine will be utilized to support the application of the MCLCA in order to evaluate the building systems in a condominium building, which is outlined in detail in the following section.

4.2.3 The application of the MCLCA framework

The case study presented in Section 4.1 uses a single-family house to demonstrate the application of the proposed framework. However, the application of MCLCA is not limited to single-family housing units but can be used to assess other type of buildings. Case study 4.2 utilizes the MCLCA framework to assess building systems of a condominium building presented in Figure 4-23.

Figure 4-23 3D rendering of Case Study 2 building

The building consists of five floors, non-accessible attic, and an underground parkade as outlined in Table 4-18.

Table 4-18 Floor division of Case Study 2 building

Floor	Area (ft^2)	Unit Count			
		1BDRoom of 475 ft^2	2BDRoom of 695 ft^2	2BDRoom of 698 ft^2	2BDRoom of 1,041 ft^2
Parkade	14,630	N/A			
Main	14,630	11	3	4	1
Second	14,630	11	3	4	1
Third	14,630	11	3	4	1
Forth	14,630	11	3	4	1
Fifth	14,630	11	3	4	1
Roof	14,630	N/A			

This building has an estimated total cost of CA$12,667,255.00. The estimated carbon emissions during the construction phase are 1,990 t, and the amount of construction energy is 1,422,245,672 MJ. This case study will focus of the interaction between building envelope, HVAC systems (heating system), and the lighting system. In order to emphasize the interactions among the building systems, this case study will only consider building envelope components as design variables.

1. *Define the sub-components of the assessment criteria*

The breakdown of assessment criteria in this case study follows the same logic as described in Section 4.1, where each criterion is the sum of two sub-components representing construction and operation phases of the building lifecycle. Equations 4-2 to 4-4 are also applied in this case study to describe the assessment criteria breakdown.

$$C = C_{con} + C_{ops} \tag{4-2}$$

$$EC = EC_{emb} + EC_{ops} \tag{4-3}$$

$$CeM = CeM_{con} + CeM_{eops} \tag{4-4}$$

2. *Define the design variables*

In this case study only building envelope components are considered as variables, as the focus is to incorporate more building systems into the study of the interactions between the design variables and other building components. Therefore, the design variables of this case study are as follows:

- window type (WT_i), where values can be double-pane or triple-pane;
- window-to-wall ratio (WWR_i);
- R-value for walls (WRV); and,
- R-value for roof (RRV_i).

Note that the subscript, i, indicates the geographical direction the façade of the studied building faces, and, therefore, $i \in \{N, S, E, W\}$.

3. *Define the interactions between the design variables and the sub-components of the assessment criteria*

- **Define the interactions during the construction phase**
    - The interactions between the design variables and construction cost*:*

As explained previously in Section 4.1, the cost associated with the construction of the building can be evaluated as a function of the quantities of material used and their unit prices, which is described in Equation 4-5. Equation 4-5 can be rewritten to accommodate the selected design variables as follows:

$$C_{con} = \sum WWR_i \times WA_i \times UP_{WT_i} + UP_{WRV/SF} \times \sum FA_j + UP_{RRV/SF} \times RFA + 11{,}452{,}700 \quad (4\text{-}69)$$

The sum of CA$11,452,700.00 in Equation 4-69 is the remainder of subtracting the cost portions associated with the design variables from the total estimated cost of the building. The variables expressed in the equations in this section are equal to those in Equation 4-6.

- The interactions between the design variables and embodied energy:

Like construction cost, embodied energy is a function of the material used and their quantities, where Equation 4-7 demonstrates this function (see Section 4.1). The embodied energy as a function of the selected design variables is described in Equation 4-70.

$$EC_{emb} = \sum WWR_i \times WA_i \times UEE_{WT_i} + UEE_{WRV/SF} \times \sum FA_j + UEE_{RRV/SF} \times RFA + 1{,}280{,}021{,}105 \quad (4\text{-}70)$$

The notation used in Equation 4-7 applies to Equation 4-70.

- The interactions between the design variables and embodied carbon:

The same logic applied to both construction cost and embodied energy is used to derive Equation 4-71, which links the design variables with the carbon footprint of the building, as follows.

$$CeM_{fp} = \sum WWR_i \times WA_i \times UEC_{WT} + UEC_{WRV/SF} \times \sum FA_j + UEC_{RRV/SF} \times RFA + 1790 \quad (4\text{-}71)$$

where

- $UEC_{WRV/SF}$ denotes the amount of embodied carbon associated with insulating 1 ft^2 of the house to achieve a certain WRV.

- $UEC_{RRV/SF}$ denotes the amount of embodied energy associated with insulating 1 ft^2 of roof footprint to achieve a given RRV.

- **Define the interactions during the operation phase**

As per the discussion presented in Section 4.1, operational cost can be expressed as shows in Equation 4-31.

$$C_{ops} = C_{fuel} + C_{elec} \tag{4-31}$$

Energy analysis indicates the **annual** operational cost as presented in Table 4-19.

Table 4-19 Annual operational cost of the original design

Annual Elec. Cost (CA$)	Annual Fuel Cost (CA$)	Total Operational Cost (CA$)
47,030.00	38,830.00	85,860.00

Note that the figures presented in Table 4-19 represent the cost of energy consumed in the building due to all occupant activities, which include, but are not limited to, space heating, water heating, lighting, cooking, etc.

Where Equations 4-32 and 4-33 represent the annual operational energy and carbon emissions, respectively, energy analysis indicates that the energy demand during operation is as per Table 4-20.

Table 4-20 Annual energy consumption of the original design

Annual Electricity demand (kWh)	Annual Fuel demand (MJ)	Total Energy Demand (MJ)
462,393	5,973,909	7,638,524

Additionally, the annual CO_2 emissions due to the consumed energy is estimated to be 475 t.

4. Develop the aggregated functions of the assessment criteria

The aggregated functions are obtained by substituting the right-hand side of Equations 4-2 to 4-4 by their correspondent values from Equations 4-69 to 4-71 and Equations 4-31 to 4-33 to the aggregated functions.

Substituting Equations 4-69 and 4-31 in Equation 4-2 leads to cost aggregated function as follows:

$$C = \sum WWR_i \times WA_i \times UP_{WT_i} + UP_{WRV/SF} \times \sum FA_j + UP_{RRV/SF} \times RFA + C_{fuel} + C_{elec} + 11{,}452{,}700 \quad (4\text{-}72)$$

The energy aggregated function is formed by substituting Equations 4-70 and 4-32 in Equation 4-3 as follows:

$$EC = \sum WWR_i \times WA_i \times UEE_{WT_i} + UEE_{WRV/SF} \times \sum FA_j + UEE_{RRV/SF} \times RFA + EC_{fuel} + EC_{elec} + 1{,}280{,}021{,}105 \quad (4\text{-}73)$$

Finally, the aggregated function of carbon emissions as a result of Equations 4-3, 4-33, and 4-71 is as follows:

$$CeM_{emb} = \sum WWR_i \times WA_i \times UEC_{WT} + UEC_{WRV/SF} \times \sum FA_j + UEC_{RRV/SF} \times RFA + CeM_{fuel} + CeM_{elec} + 1790 \quad (4\text{-}73)$$

The following step is to derive the aggregated functions, making it possible to solve for the fittest solution.

5. Derive the aggregated functions according to each of the design variables

The resulting change during the operational phase caused by a change in the design variable is assessed using the developed energy analysis tool, while it is assessed manually during the construction phase.

- **Cost aggregated function**

As per Equation 4-36 the total change in the construction cost is the total sum of all the changes caused by the changes in the design variables. Table 4-21 demonstrates the change each design variable creates.

Table 4-21 Change in the construction cost due to changes in design variables

Design Variable	Change	ΔC_{con_i}
WT (initial state: double-glazed)	Increase of CA$ 5.78 for triple-glazed No change in the quantities	$Wall - Area \times Q_{WWR} \times \Delta UP_{WT}$
WWR (assessed for each façade)	Changes the area of the glazes portion of the walls	$Wall - Area \times \Delta Q_{WWR} \times UP_{WT}$
WRV	Changes the quantities/quality of insulation materials	$\Delta UP_{WRV/SF} \times \sum FA_j$
RRV	Changes the quantities/quality of insulation materials	$\Delta UP_{RRV/SF} \times RFA$

Changes in cost during the operational phase are controlled by Equation 4-37 that reads:

$$\Delta C_{ops} = \sum_{i=1}^{m} \Delta C_{fuel_i} + \sum_{i=1}^{m} \Delta C_{elec_i} \qquad (4\text{-}37)$$

Using the fitting described previously in Section 4.1, the following results are presented in Table 4-22.

Table 4-22 Change in operational cost due to changes in design variables

Design Variable	**Location**	ΔC_{fuel_i}	ΔC_{elec_i}
WT[1]	N	$0.0007WWR_N + 0.0007$	$0.0003WWR_N + 0.0003$
	S	$0.0007WWR_S + 0.002$	$-3\times10^{-6}{WWR_S}^2 + 0.0003WWR_S + 0.0001$
	W	$0.0004WWR_W + 0.0011$	$-1\times10^{-6}{WWR_W}^2 + 0.0002WWR_W + 1\times10^{-6}$
	E	$-1\times10^{-6}{WWR_E}^2 + 0.0005WWR_E - 7\times10^{-7}$	$9\times10^{-8}{WWR_E}^3 - 2\times10^{-5}{WWR_E}^2 + 0.0008WWR_E - 6\times10^{-6}$
WWR	N	$22.93WWR_N - 502.66$	$27.04WWR_N - 356.7$
	S	$0.36{WWR_S}^2 - 38.1WWR_S - 367.21$	$0.77{WWR_S}^2 + 15.8WWR_S - 156.49$
	W	$0.17{WWR_W}^2 - 6.9WWR_W - 248.5$	$0.27{WWR_W}^2 + 30.8WWR_W - 168.47$
	E	$0.17{WWR_E}^2 - 0.3WWR_E - 379.29$	$0.6{WWR_E}^2 - 10.5WWR_E - 220$
WRV	N/A	$5.1WRV^2 - 637WRV + 4782$	$3.98WRV^2 - 370WRV + 3460$
RRV	N/A	$0.94RRV^2 - 102.83RRV + 1955$	$0.645RRV^2 - 67.51RRV + 1317$

[1]the equations shown in the table control the percentage by which the cost of fuel and electricity is reduced when using triple-glazed windows rather than double-glazed.

Based on Tables 4-21 and 4-22 the derivatives of the aggregated cost function according to each of the variables are demonstrated in Table 4-23.

Table 4-23 Change in cost due to changes in design variables

Design Variable	Location	ΔC_i	Equation Number
WT[1]	N	$WA_N \times WWR_N \times \Delta UP_{WT} + (0.001WWR_N + 0.001) \times YR \times 85860$	(4-74)
	S	$WA_S \times WWR_S \times \Delta UP_{WT} + (-3 \times 10^{-6}{WWR_S}^2 + 0.001WWR_S + 0.0021) \times YR \times 85860$	(4-75)
	W	$WA_W \times WWR_W \times \Delta UP_{WT} + (-1 \times 10^{-6}{WWR_W}^2 + 0.0006WWR_W + 0.0011) \times YR \times 85860$	(4-76)
	E	$WA_E \times WWR_E \times \Delta UP_{WT} + (-9 \times 10^{-8}{WWR_E}^3 - 2 \times 10^{-5}{WWR_E}^2 + 0.0013WWR_E) \times YR \times 85860$	(4-77)
WWR	N	$WA_N \times \Delta Q_{WWR_N} \times UP_{WT} + (50WWR_N - 840) \times YR$	(4-78)
	S	$WA_S \times \Delta Q_{WWR_S} \times UP_{WT} + ({WWR_S}^2 - 22WWR_S - 423.7) \times YR$	(4-79)
	W	$WA_W \times \Delta Q_{WWR_W} \times UP_{WT} + (0.44{WWR_W}^2 - 37.7WWR_W - 417) \times YR$	(4-80)
	E	$WA_E \times \Delta Q_{WWR_E} \times UP_{WT} + (0.44{WWR_W}^2 - 37.7WWR_W - 417) \times YR$	(4-81)
WRV	N/A	$\Delta UP_{WRV/SF} \times \sum FA_j + (9WRV^2 - 707WRV + 8242) \times YR$	(4-82)
RRV	N/A	$\Delta UP_{RV/SF} \times RFA + (1.5RRV^2 - 170RRV + 3272) \times YR$	(4-83)

- **Energy Consumption aggregated function**

As presented earlier in Section 4.1, the contribution of windows to the overall embodied energy is marginal and can thus be ignored; additionally, any changes resulting from changing the size of windows or the glazing type can also be ignored. Furthermore, changing the thermal resistance of exterior walls and the roof can be achieved by several methods such as increasing the thickness of the insulation or using different insulation material. Due to this variation, the time and effort required to accurately assess the changes in the embodied energy can increase considerably. Therefore, changes in the embodied energy due to the changes in the thermal resistance values of exterior walls and the roof will be ignored. Based on the presented argument, the changes in the embodied energy due to changes in the design variables are ignored, and the change in the energy consumption can be written as per Equation 4-48.

$$\Delta EC = \Delta C_{ops} = \sum_{i=1}^{m} \Delta EC_{fuel_i} + \sum_{i=1}^{m} \Delta EC_{elec_i} \quad (4\text{-}84)$$

Based on the energy analysis tool and Equation 4-84, the derivatives of the energy consumption aggregated function according to design variable are given in Table 4-24.

Table 4-24
Change in energy consumption due to changes in design variables

Design Variable	Location	$\Delta \boldsymbol{EC_i}$	Equation Number
WT	N	$\left(7 \times 10^{-6} WWR_E{}^3 - 0.0013 WWR_N{}^2 + 0.07 WWR_N\right) \times YR \times 7638524$	(4-85)
	S	$(0.0006 WWR_W{}^3 - 0.07 WWR_S{}^2 + 1.7 WWR_S) \times YR \times 7638524$	(4-86)
	W	$(-5 \times 10^{-6} WWR_W{}^3 + 0.0009 WWR_W{}^2 + 0.05 WWR_W) \times YR \times 7638524$	(4-87)
	E	$(3 \times 10^{-5} WWR_E{}^3 - 0.004 WWR_E{}^2 + 0.2 WWR_E) \times YR \times 7638524$	(4-88)
WWR	N	$(961 WWR_N - 12700) \times YR$	(4-89)
	S	$(27.41 WWR_S{}^2 + 553.12 WWR_S - 5593) \times YR$	(4-90)
	W	$(9.75 WWR_W{}^2 + 1090 WWR_W - 6000) \times YR$	(4-91)
	E	$(21.15 WWR_E{}^2 - 372 WWR_E + 7836) \times YR$	(4-92)
WRV	N/A	$(141.5 WRV^2 - 13166 WRV + 123151) \times YR$	(4-93)
RRV	N/A	$(23 RRV^2 - 2405 RRV + 46884) \times YR$	(4-94)

Note: YR is the duration of the operational phase measured in years.

- **Carbon Emissions aggregated function**

The argument presented previously to justify ignoring the changes in the embodied energy also applies to the carbon footprint, and, therefore, changes to the carbon footprint due to changes in the design variable values are to be ignored. Therefore, Equation 4-95 is correct.

$$\Delta CeM = \Delta CeM_{ops} \tag{4-95}$$

Based on the performed energy analysis and Equation 4-95, the derivatives of the carbon emissions aggregated function according to the design variable are given in Table 4-25.

Table 4-25 Change in emitted carbon due to changes in design variables

Design Variable	Location	ΔCeM_i	Equation Number
WT	N	$(0.0006WWR_N + 0.0005) \times YR \times 475$	(4-96)
	S	$(9 \times 10^{-6}{WWR_S}^2 + 6 \times 10^{-7}WWR_S + 0.0004) \times YR \times 475$	(4-97)
	W	$(4 \times 10^{-6}{WWR_W}^2 + 0.0002WWR_W + 0.0003) \times YR \times 475$	(4-98)
	E	$(4 \times 10^{-6}{WWR_E}^2 + 0.0002WWR_E) \times YR \times 475$	(4-99)
WWR	N	$(0.3WWR_N + 470) \times YR$	(4-100)
	S	$(0.7WWR_S - 434) \times YR$	(4-101)
	W	$(0.5WWR_W - 455) \times YR$	(4-102)
	E	$(0.5WWR_W + 455) \times YR$	(4-103)
WRV	N/A	$(0.05WRV^2 - 6.3WRV + 49) \times YR$	(4-104)
RRV	N/A	$(0.01RRV^2 - 1.04RRV + 19.1) \times YR$	(4-105)

Note that, since the amount of emitted CO_2 is assessed on an annual basis, YR indicates the number of years over which the building is assessed.

6. *Define the technical performance measure to use and assess the design variables against one another*

The performance measure used in this research is the failure model as described in reliability theory practice, where the evaluated system has two states: functioning and broken. As per the failure model, the system performs as initially designed until it fails, and then it must be replaced; for this reason, the cost of maintenance was not considered previously.

Failure patterns are controlled by the survivor function (which was explained in Section 3.2.1.) The survivor function in the failure model describes the probability of a system's failure in a given time frame and is usually formulated based on the historical failure data of similar systems and/or data from the manufacturer.

This section demonstrates how to find the survivor function of the boiler in a heating system of a multi-family residential building using historical data retrieved from ASHRAE's owning and operating database (http://xp20.ashrae.org/publicdatabase/). The retrieved data is presented in Table 4-26.

Table 4-26 Equipment failure data obtained from ASHRAE

Equipment ID	System Type	Floor Area (ft^2)	Install Year	Removal Year	TEGR (MJ)
2978	Heating	456,000	1993	2001	53,370,240
2987	Heating	85,800	1994		
2944	Heating	58,345	1996		
2979	Heating	569,172	1993	2001	66,615,891
2962	Heating	88,000	1990		
2977	Heating	25,000	1993	2001	2,926,000
2829	Heating	160,000	1992		
2985	Heating	58,500	1994		
2946	Heating	153,800	1970	1993	51,752,162
2866	Heating	27,090	1976	2001	9,908,168
2865	Heating	183,216	1976	2001	67,011,252
2867	Heating	31,320	1976	2001	11,455,290
2980	Heating	646,800	1993	2001	75,701,472
2865	Heating	183,216	1976	2001	67,011,252
2866	Heating	27,090	1976	2001	9,908,168
2867	Heating	31,320	1976	2001	11,455,290
2946	Heating	153,800	1970	1993	51,752,162
2977	Heating	25,000	1993	2001	2,926,000
2978	Heating	456,000	1993	2001	53,370,240
2979	Heating	569,172	1993	2001	66,615,891
2980	Heating	646,800	1993	2001	75,701,472

Note that total energy generated before removal (TEGR) is excluded from the retrieved data and was calculated considering that the boiler generates 14.63 MJ/ft^2/year using Equation 4-106.

$$TEGR = 14.62 \times floor\_Area \times (Removal_{Year} - Install_{Year}) \tag{4-106}$$

TEGR represents the amount of energy the boiler generates before it fails. Therefore, finding the fitting distribution of the presented sample leads to formulating the survivor function that represents the probable failure of the boiler.

Using EasyFit to find the distribution data reveals that, according to the Kolmogorov-Smirnov test for goodness of fit, beta distribution ranks first. Figure 4-24 presents the probability density function of the data sample.

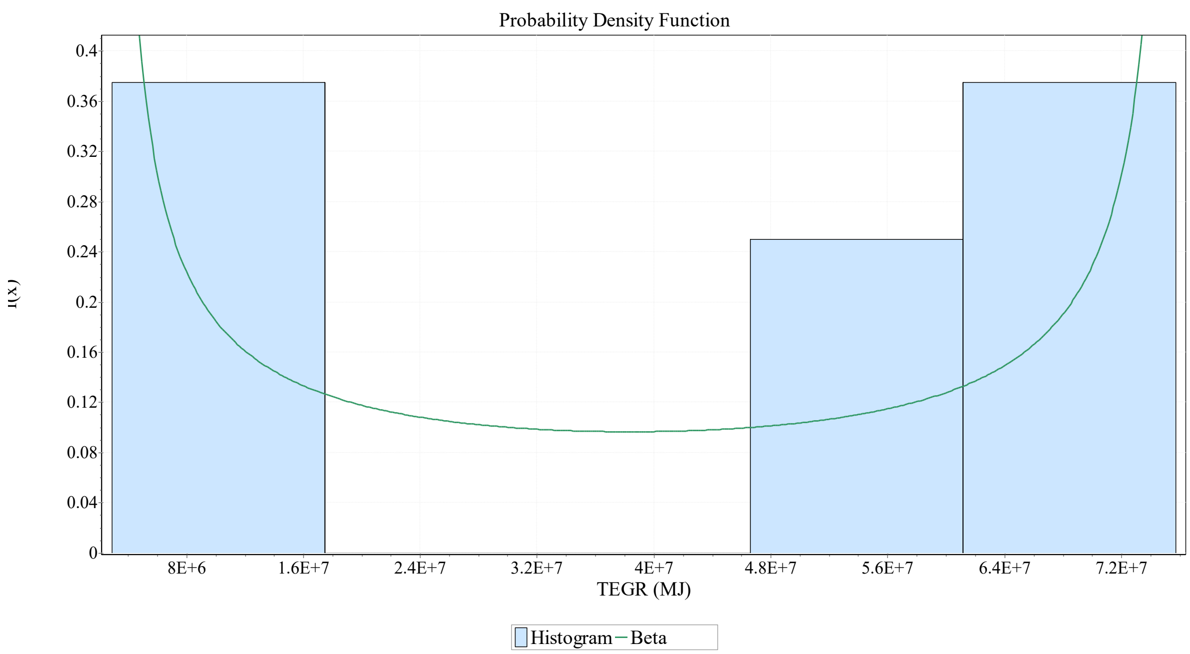


Figure 4-24 Data fitting and correspondent beta function

Figure 4-25 presents the beta survivor function compared to the sample.

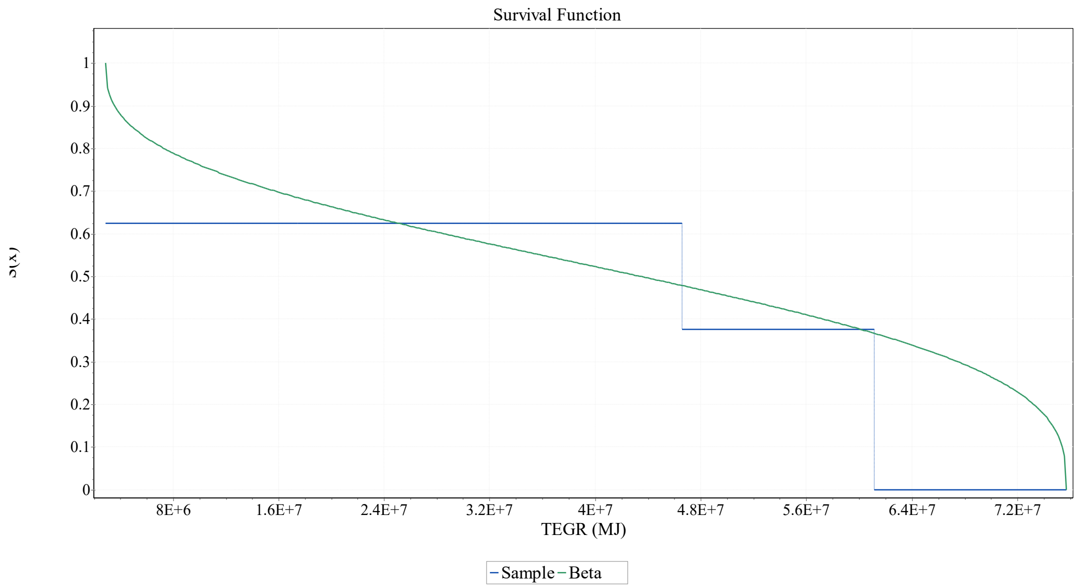


Figure 4-25 Beta survivor function of the sample

Beta distribution parameters for this sample are as follows:

$$\propto = 0.35809 \qquad \beta = 0.32408$$

$$a = 2.9260 \times 10^{6} \qquad b = 7.5701 \times 10^{7}$$

The general formula for the probability density function of beta distribution is as follows (NIST 2013):

$$f(x) = \frac{(x-a)^{\propto -1}(b-x)^{\beta-1}}{B(\alpha,\beta)(b-a)^{\alpha+\beta-1}} \tag{4-107}$$

B(α,β) is calculated as per Equation 4-108.

$$B(\alpha,\beta) = \int_0^1 t^{\alpha-1}(1-t)^{\beta-1}dt \tag{4-108}$$

Substituting the values of *α* and *β* of the sample in Equation 4-108 results in *B(α,β)=5.16863*, and the probability density function for the sample can be expressed as follows:

$$f(x) = \frac{61.0096}{(x - 2.9260 \times 10^6)^{0.64191} \times (7.5701 \times 10^7 - x)^{0.67592}} \tag{4-109}$$

Now, the survivor function is calculated as follows:

$$R(t) = \int_t^\infty f(x).dx = \int_t^\infty \frac{61.0096}{(x - 2.9260 \times 10^6)^{0.64191} \times (7.5701 \times 10^7 - x)^{0.67592}} dx$$

which leads to

$$\begin{aligned} &R(t) \\ &= 170.375 \times (x - 2.9260 \times 10^6)^{0.35809} \\ &\times (1.04020 - 1.3741 \times 10^{-8} x)^{0.67592} \\ &\times \frac{{}_2F_1(0.35809, 0.67592; 1.35809;\ 1.3741 \times 10^{-8} \times (x - 2.9260 \times 10^6))}{(7.5701 \times 10^7 - x)^{0.67592}} \end{aligned} \tag{4-110}$$

As the survivor function is known, the MTTF can be calculated using Equation 3-6.

$$MTTF = \int_0^\infty R(t).dt \approx\ 42{,}343{,}000\ MJ$$

This indicates that the boiler is expected to generate 42,343,000 MJ of energy before its removal due to failure. In the failure model of reliability theory, as explained earlier, the modelled system is assumed to perform as designed until it fails, which implies that the definition of performance as per this model is either that the system is functioning or not. Therefore, the number of years before removal is equivalent to the system's performance, of which designers and stakeholders seek to improve by selecting better design alternatives, i.e., increase the number of years before removal. Thus, for the case of the presented boiler, the values of design variables must be chosen to reduce the heat load, which will reduce the amount of energy that should be generated, leading to a longer life span for the boiler and therefore a better-performing boiler.

In this case study, two systems will be evaluated: the heating system represented by the boiler, and the lighting system.

- **Heating system with lighting system and design variables**

Since the boiler is the equipment in the case study heating system that causes a full shutdown of the system when it fails, it will be used to represent the heating system when assessing the influence of building components on the heating system. The boiler features the survivor function as expressed in Equation 4-110, which is associated with an MTTF of 42,343,000 MJ. The life span of the boiler is assessed using Equation 4-64. Given that the change a variable produces in a function is the derivative of that function according to the variable, the change a design variable and/or other systems causes on the performance of the boiler (i.e., the boiler's life span as per the model selected for performance assessment) is expressed in Equation 4-111.

$$\Delta yr_i = \frac{-(\Delta Annual\ Energy\ Demand_i) \times 42343000}{Annual\ Energy\ Demand^2} \tag{4-111}$$

where

- Δyr_i represents the change in the boiler's performance due to the change in building component *i*; and,
- $\Delta Annual\ Energy\ Demand_i$ represents the change in the annual energy demand on the heating system due to the change in building component *i.*

While the selected design variables have an obvious impact on the energy demand of the building, the lighting system indirectly affects the energy demand by increasing the internal heat gain as discussed earlier. However, as per ASHREA (2013), the lighting fixtures in residential buildings have marginal impact on the heat gain, and therefore can be disregarded. Based on Table 4-24 and Equation 4-111, changes in the boiler's performance due to the changes in the design variables are demonstrated in Table 4-27.

Table 4-27 Changes in boiler's performance due changes in design variables

Design Variable	**Location**	$\Delta \boldsymbol{yr_i}$	**Equation Number**
WT	N	$2.471 \times \left(7 \times 10^{-6} WWR_E{}^3 - 0.0013 WWR_N{}^2 + 0.07 WWR_N\right)$	(4-112)
	S	$2.471 \times (0.0006 WWR_W{}^3 - 0.07 WWR_S{}^2 + 1.7 WWR_S)$	(4-113)
	W	$2.471 \times (-5 \times 10^{-6} WWR_W{}^3 + 0.0009 WWR_W{}^2 + 0.05 WWR_W)$	(4-114)
	E	$2.471 \times (3 \times 10^{-5} WWR_E{}^3 - 0.004 WWR_E{}^2 + 0.2 WWR_E)$	(4-115)
WWR	N	$(961 WWR_N - 12700) \times 2.862 \times 10^{-6}$	(4-116)
	S	$(27.41 WWR_S{}^2 + 553.12 WWR_S - 5593) \times 2.862 \times 10^{-6}$	(4-117)
	W	$(9.75 WWR_W{}^2 + 1090 WWR_W - 6000) \times 2.862 \times 10^{-6}$	(4-118)
	E	$(21.15 WWR_E{}^2 - 372 WWR_E + 7836) \times 2.862 \times 10^{-6}$	(4-119)
WRV	N/A	$(141.5 WRV^2 - 13166 WRV + 123151) \times 2.862 \times 10^{-6}$	(4-120)
RRV	N/A	$(23 RRV^2 - 2405 RRV + 46884) \times 2.862 \times 10^{-6}$	(4-121)

- **Lighting system and design variables**

The artificial lighting design for interior spaces is dependent upon the size of the space and the amount of natural illumination the space receives through fenestration. Given that the size of the building is among the variables to be evaluated, in this case study, the changes in the lighting demand are assessed only against changes in the fenestration variables. Also, adding an extra layer of high-transparency glass is results in a marginal change compared to changes in the fenestration area, and therefore, changes in the lighting demand will be assessed against changes in WWR. Using GBS® to assess the lighting demand changes (ΔLD) due to changes in the WWR values leads to the results presented in Table 4-28.

Table 4-28 Changes in lighting demand due to changes in design variables

Design Variable	Location	$\Delta \boldsymbol{LD_i}$	Equation Number
WWR	N	$4 \times 10^{-7} WWR_N{}^3 - 3 \times 10^{-5} WWR_N{}^2 - 0.0028 WWR_N$	(4-122)
	S	$-8 \times 10^{-5} WWR_S{}^2 - 0.0011 WWR_S$	(4-123)
	W	$1 \times 10^{-5} WWR_W{}^3 - 0.0013 WWR_W{}^2 + 0.024 WWR_W$	(4-124)
	E	$-4 \times 10^{-5} WWR_E{}^3 - 0.0005 WWR_E{}^2 - 0.02 WWR_E$	(4-125)

As can be observed from Equations 4-122 to 4-125, the changes in the lighting demand due to changes in the WWR value are minor, which justifies disregarding these changes.

7. *For each design variable, find the alternative that best fits the correspondent derived functions and satisfies performance measures.*

The case study presented in Section 4.1 demonstrates two methods to find the fittest value for the design alternatives—MOO and MAUT—in order to reduce the values of the assessment criteria (i.e., lifecycle cost, lifecycle energy consumption, and lifecycle CO_2 emissions) and improve the performance of the selected system (i.e., the heating and lighting systems). This case study uses MOO only to find the desired values for the design variables. Table 4-29 presents the set of objectives to be optimized for each of the design variables.

Table 4-29 MOO objectives and solutions

Design Variable	Location	Objectives (Increase the change in Equations:)	Fittest Value
WT	N	4-74, 4-85, 4-96, and 4-112	TPL
	S	4-75, 4-86, 4-97, and 4-113	DBl
	W	4-76, 4-87, 4-98, and 4-114	TPL
	E	4-77, 4-88, 4-99, and 4-115	DBl
WWR	N	4-78, 4-89, 4-100, and 4-116	0.54
	S	4-79, 4-90, 4-101, and 4-117	0.58
	W	4-80, 4-91, 4-102, and 4-118	0.35
	E	4-81, 4-92, 4-103, and 4-119	0.64
WRV	N/A	4-82, 4-93, 4-104, and 4-120	26
RRV	N/A	4-83, 4-94, 4-105, and 4-121	32

Table 4-30 presents a comparison between the values of assessment criteria before and after incorporating the proposed changes where OD stands for original design and PC stands for proposed changes.

Table 4-30 Comparison between impacts of original design and proposed changes on assessment criteria and performance

		OD	PC	Difference	Comments
Cost (CA$)	Construction	12,667,255	12,717,255	0.39%	Extra spending
	Operation (Annual)	85,860	80,945	5.72%	Savings
Carbon Emission (Metric tonnes)	Construction	1,990	1,990	N/A	
	Operation (Annual)	475	391	17.68%	Emissions reduction
Energy Consumption (MJ)	Construction	1,422,245,672	1,422,245,672	N/A	
	Operation (Annual)	7,638,524	7,086,078	7.23%	Reduced consumption
Boiler Performance (yrs.)		8	9	12.50%	Improving performance

Table 4-30 indicates that the proposed changes increase the construction cost by 0.39% while reducing the operational cost by 5.72%. This indicates that in 10 years of operations the savings in operational cost offsets the upfront investment, and in 30 years of operations the savings in operational cost totals 1% of the original construction cost. Table 4-30 also reveals that the reduction in CO_2 is the greatest change among all other assessment criteria, followed by a 12.5% increase in the life span of the boiler, and a 7.23% reduction in energy consumption. The findings of implementing the MCLCA framework to a mid-rise building in this case study demonstrate that the proposed framework is flexible enough to be implemented in various types of buildings, and is capable of achieving considerable reduction in the impact of the building on the assessment criteria while improving the performance of selected systems as per selected performance models.

The case studies presented in Sections 4.1 and 4.2 aim to provide a full-scale application of the methodology proposed in Section 3-2. The primary goal is to present the application steps in detail in a manner that practitioners can relate to and apply to their own real-life scenarios. As can be seen from the examples presented in these case studies, the proposed method provides solid groundwork for extending the assessment process beyond using one assessment criterion toward a more inclusive approach. This method of approaching the design of the elements allows practitioners to better understand how their design decisions may affect the work of others. It also helps the construction industry to be more sustainable due to the multi-objective assessment platform sustainability requires.

4.3. Case Study 3: the application of the value-visualization framework

The building presented in Figure 4-26 is a proposed design for a laboratory and is used to demonstrate the function of the visualization framework. However, while this example outlines the steps and findings of each phase of the framework for illustrative purposes, these steps are in fact automated within the framework and thus the user sees the final appearance adjustments only. For this proposed building design, the case study visualizes cost, energy consumption, and CO_2 emissions for the structural elements. Note that, for the purpose of assessing the energy consumption and CO_2 emissions prior to operations, embodied energy and CO_2 are used. The systems used in the building are as follows:

- Building envelope
    a. Structural insulated panels (SIP) for the exterior walls, thermal resistance
    b. Double-glazed windows, thermal resistance
    c. Flat roof insulation
- Structural systems
    a. Steel deck on steel joist system for roof
    b. Wood deck on Glued-laminated wood joist system for floors
    c. Pre-cast prestressed concrete girders and Glued-laminated wood beams for roof beams
    d. Glued-laminated wood for floor beams
    e. Combination of steel and concrete columns for vertical structural elements
- HVAC systems
    a. Efficient 12 SEER, 90% AFUE furnace split system with gas heat
    b. Forward curved constant volume fan and premium efficiency motor

c. 2.0 inch of water gauge (498 pascals) static pressure Constant Volume duct system

d. Integrated differential dry-bulb temperature economizer

e. Domestic hot water unit (0.575 Energy Factor)

This case study visualizes values as follows: red (0,1,0.5) is assigned to cost, yellow (60,1,0.5) to energy consumption, and green (120, 1, 0.5) to CO_2 emissions. It should be noted that, according to this assignment (i.e., red for cost, yellow for energy consumption, and green for carbon emissions), V1, V2, and V3 in Figure 3-8 represent cost, energy consumption, and CO_2 emissions, respectively.

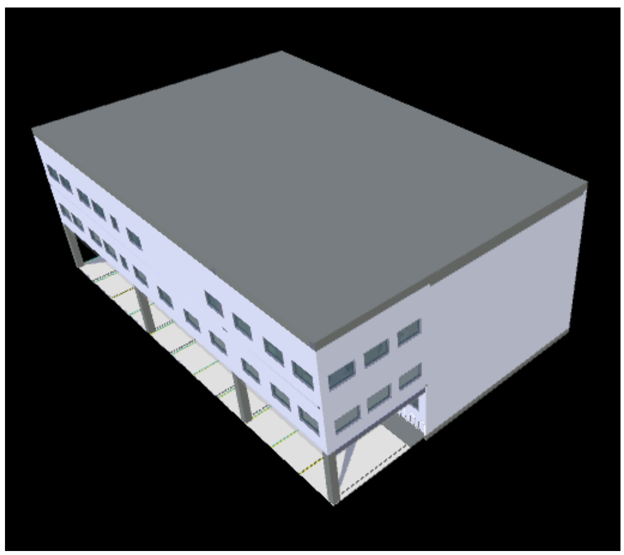


Figure 4-26 Example building

1. *Assessing element contribution*

Two different databases are used to assess the contributions of elements to each of the selected values: (1) RSMeans® data from GORDIAN for cost data, and (2) ICE database (Circular Ecology 2011) for embodied energy and carbon. Table 4-31 presents the row contributions of the selected elements.

Table 4-31 Row contributions of elements

Elements	Cost	EE (MJ)	CO_2 EM (t)
Wood Joists	$25,316.70	41,580	3,014.55
Concrete Columns	$6,793.45	5,060	351.175
Precast Beams	$45,522.96	163,944	11,378.07
Steel Joists	$19,782.29	79,066	4,379.04
Steel Deck	$27,577.15	163,856	10,074.24
Glued-laminated Beams	$15,299.04	64,330	4,663.92

The totals of values are given in Table 4-32.

Table 4-32 Value totals

Phase	Cost (CA$)	Energy (MJ)	CO_2 Emissions (t)
Construction	1,712,325 (as per RSMeans data)	13,052,100 (as per Jackson (2005))	230 (as per Build Carbon Neutral (2007))
Operations	Lifecycle: 257,812 Annual: 18,929	Lifecycle: 44,621,248 Annual: 1,487,376	Lifecycle: 1,372 Annual: 98

It should be noted that lifecycle is considered to be 13 years in this example, thus all the elements are covered by their initial warranties within this timeframe. As a result, the operational cost does not include maintenance. It should also be noted that energy analysis is performed using Autodesk Green Building Studio®.

It is also important to note that during the development and the experimentation of the framework, normalizing the row contributions of a given element using the contribution of their respective discipline provides easier-to-interpret visual results. Therefore, it is better practice to visualize first the contribution of disciplines as one unit (e.g., structural or mechanical), then to visualize the element contribution as a percentage of the corresponding discipline contribution. Assuming a structural element with a row contribution of s_{ij} to a value (j), then the row contribution of all structural elements in the building is S_j, where

$$S_j = \sum_{i=1}^{n} s_{ij} \tag{4-125}$$

Therefore, Equation 4-125 for a structural element of a contribution (s_{ij}) to value j is expressed as,

$$G_{ij} = \frac{s_{ij}}{S_j} \times W_j \tag{4-126}$$

Based on Equation 4-126, where $Wj = 1$ for all values, Tables 4-31, and 4-32, the graded contributions for each of the elements at each of the lifecycle phases are presented in Table 4-33.

Table 4-33 Graded contribution of elements

Elements	**at t1**			**at t2**			**at t3**		
	Graded Contribution per Value			Graded Contribution per Value			Graded Contribution per Value		
	Cost	EC	CO_2 EM.	Cost	EC	CO_2 EM.	Cost	EC	CO_2 EM.
Wood Joists	0.1641	0.0803	0.0742	0.1492	0.0396	0.0683	0.1434	0.0324	0.0113
Concrete Columns	0.0440	0.0098	0.0086	0.0400	0.0048	0.0080	0.0385	0.0039	0.0013
Precast Beams	0.2950	0.3166	0.2800	0.2683	0.1563	0.2579	0.2579	0.1276	0.0428
Steel Joists	0.1282	0.1527	0.1078	0.1166	0.0754	0.0993	0.1121	0.0615	0.0165
Steel Deck	0.1787	0.3164	0.2479	0.1625	0.1562	0.2283	0.1562	0.1275	0.0379
Glued-laminated Beams	0.0991	0.1242	0.1148	0.0902	0.0613	0.1057	0.0867	0.0501	0.0176

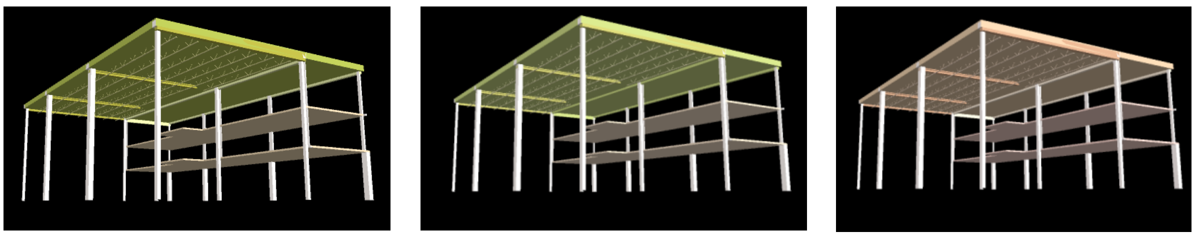
2. *Visualization matrix*

As per Section 3.4.3.1.3 and based on Table 4-33, Table 4-34 presents the visualization colour of each of the elements at each phase (Note Table 4-34 presents colours).

Table 4-34 Visualization matrix

Element	at t1	at t2	at t3
Wood Joists			
Concrete Columns			
Precast Beams			
Steel Joists			
Steel Deck			
Glued-laminated Beams			

The visualization matrix in Table 4-34 is used in the framework as a reference to change the colours of the elements throughout the visualization process; the end user neither deals with or sees this matrix. This matrix is automatically visualized in the BIM environment as presented in Figure 4-27.



(a) (b) (c)

Figure 4-27 Lifecycle value visualization of the example building at (a) t1, (b) t2, and (c) t3

The question now is determining how to interpret these results. First, it should be noted that the colours of elements fade as time elapses. This indicates that the collective contributions of these elements to the values decay over time, which informs the user that once construction is completed these elements become less influential on values. Therefore, designers must focus on these elements to reduce the construction cost, embodied energy, and embodied carbon, but then their attention must shift toward other elements in order to reduce the operational cost, consumed energy, and emitted carbon. At each assessment point, the roof system components have darker colours than other elements, which indicates that their collective contribution to the selected values (i.e., cost, energy consumption, and CO_2 emission) is larger than the contribution of other elements with lighter colours, and therefore refining the design of these elements has greater impact on the reduction of overall building impact on the values. The pale red colour of the Glued-laminated beams (located on the right side of the slab in Figure 4-27) indicates that these beams contribute primarily to cost.

As presented by this case study, the framework provides a method for rapid assessment for the building component contributions to the selected values through visualization. Visualizing the influence of the elements on the values guides the designers toward the areas to which their design efforts should be focused in order to lower the building's impact on the studied values. This reduces the number of design iterations required to reach the desirable impact on stakeholder values, and ensures the correct values are added to the proper components.

5. Conclusion

5.1. Conclusion

The efficiency of the various systems being installed in buildings is continuously improving; however, the design of these systems continues to be done independently despite the recommendations for adapting a holistic design approach. This holistic approach accounts for the interactions among these systems on the component level, in addition to the designer level. In other words, this approach underscores the effect of design decisions on the performance of building systems during operation. On the other hand, stakeholder requirements are shifting toward a multi-criteria evaluation in order to adhere to the current sustainability requisitions. Therefore, the process of ensuring during the design phase that the required criteria will be fulfilled in the final product is becoming more complex due to the constraints that must be met. Accordingly, the construction industry needs to reconsider some of its value-adding practices to ensure that the required values are delivered at the commissioning of the project. This requires additional attention to the management of the design process as well as the evaluation method used to assess the design compliance with the design objective.

Therefore, the research presented in this thesis proposes the development of a framework that can be used to evaluate the design against multiple criteria (i.e., cost, energy consumption, and CO_2 emissions) throughout the lifecycle of a building by quantifying the interaction between its components, as illustrated in Case Studies 1 and 2. In doing so, the designers, although likely to work in silos, can receive holistic feedback on the end-product and in turn be provided an opportunity to revise their solutions. In other words, the present contribution provides an ad hoc approach to global optimization of design in the construction industry since it allows designers to understand the global impact of their solutions and by the same token provides additional information to the customer. This approach can, therefore, improve the channels of communication between all stakeholders. This framework has been tested, as shown in the case studies in Sections 4.1 and 4.2, and it has proven to contribute considerable improvement in the overall performance of the systems along with reducing the impact on stakeholder values.

On the other hand, among the various factors relating to why the construction industry is slow to advance in value-adding practices is the absence of proper tools for communicating and interpreting value. While a considerable number of studies associate this issue with the fragmentation of the construction industry, literature from other industries argues that the shortage in visualization tools to map the design elements with the necessary values to be added in a manner that reflects their impact on the overall design is a major obstacle for value adding. While BIM has brought significant advantages pertaining to nearly every aspect of the construction industry and, chiefly, has improved the visual communication among involved stakeholders, mapping the elements and their impacts is something that remains to be achieved.

The present research proposes a framework developed on the premise of bridging the gap in the construction industry regarding value visualization. It provides a practical and easy-to-use tool by which to assign the contribution of each element in a building to each of the values in the value set, to evaluate the magnitude of the contribution, and, ultimately, to map the influence of the element on the values. It satisfies the characteristics of value visualization tools as defined by the literature and complies with the process definition. The framework, due to its ability to map the impact of design outcomes on values, and its multi-value visualizing aspect, strongly supports the transformation of the construction industry to becoming more sustainable. Multiple-value visualization assists in creating a higher level of mutual and interdisciplinary collaboration and understanding, where every design team can relate to the influence their designs create on the set of considered values and the designs of other teams involved in the project.

5.2. Research Contribution

The research presented in this thesis represents a step toward embracing a more holistic approach to design for the construction industry, one that creates a balance between meeting stakeholder expectations in terms of economic and environmental consideration and the technical performance of systems in buildings. The frameworks developed as part of this research employ the system thinking philosophy to deliver tools that improve construction.

1. Academic Contribution

The construction industry is in continual pursuit of new approaches that overcome redundancy and fragmentation of the industry; the research presented in this thesis contributes to this endeavour in that it supports construction-related academic research in the following areas:

- This research contributes to the ongoing endeavor to shift scientific research from reductionism to holism.

Scientists across all disciplines have been studying natural phenomena following the path of reductionism. However, many researchers believe that this method (e.g., the Santa Fe Institute) does not support sustainable solutions because it does not consider the collective effect of the environment on studied subjects. Holism, on the other hand, does not isolate the subject from its surroundings, but analyzes the interactions between all the elements of the study. However, due to the lack of practical application, researchers are not enthusiastic to embrace its principles. This research, therefore, contributes to embracing holistic thinking in the construction industry and providing a foundation for further development.

- Embraces multi-disciplinary research in building engineering.

This research aims to eliminate segregation in engineering practices pertaining to building and construction industry products. Having all disciplines collaborating on the micro-level will enhance the quality and sustainability of the delivered research.

2. *Industrial Contribution*

The industrial importance of this research can be summarized as follows:

- Improves the performance of buildings while reducing their impact economically and environmentally.

Designing the systems in buildings in a way that considers the natural performance of these systems will ensure their effective performance. This design approach emphasizes the interdependencies among systems in buildings and optimizes resource sharing. This also guarantees the compatibility of all the components and minimizes the deficiencies in design. Moreover, as the environmental impact is one of the considered values, the deliverables of the framework would be environmentally friendly. Unlike other methods, this environmental performance will be achieved without compromising system performance nor other values such as cost. Another aspect of improving the technical performance of the building is reducing safety factors, which leads to more appealing buildings that perform better and cost less.

- Increases the likelihood of fulfilling stakeholder requirements.

The holistic procedure proposed by the present research increases stakeholder satisfaction, given that it transforms these requirements from exogenous to endogenous elements. This maximizes the probability of achieving high levels of performance and, at the same time, fulfilling stakeholder needs.

- Provides a practical tool for multi-value assessment.

Fulfilling the requirements to sustainable construction implies attaining several values simultaneously. While the value-related practice in the construction industry focuses on a single value, whether economical or environmental, this research accommodates the needs of sustainable construction through providing a practical tool that allows decision makers to assess multiple values of differing natures.

- Visualizes the impact of influence of design decision on values.

Many people tend to prefer communicating messages visually; thus, this research develops a framework that enables designers and decision makers to better understand the influence of their decisions on multiple values by means of visualization. This leads to conducting better assessments, which results in making better decisions.

5.3. Research Limitations

It is indispensable to say that the research presented in this thesis is only the starting point, albeit a necessary one due to the endless challenges confronting the construction industry, and further improvement is required in both the theoretical and practical aspects. The limitations of this research, therefore, can be summarized by the following points:

1) Due to some of the assumptions during the application process, several interdependencies are ignored in the case study, which may affect the accuracy of the findings.
2) The cumulative effect on the assessment criteria resulting from the collective change of the design variables was considered to be linear. This may not be the case in real life, and thus further investigation is required.

3) In modelling the technical performance of the HVAC systems, the failure model is used. However, other models such as the maintenance model may provide better results.
4) In modelling the technical performance of HVAC systems, these systems are treated as one system. Modelling HVAC systems as a set of interconnected systems may provide better results.
5) A major effort is required to implement the value-oriented design frame in order to declare the interdependencies among the considered components and/or values. This is still a manual process at this phase of the research development that requires a considerable amount of effort for the initial setup.
6) In both proposed frameworks, data pertaining to values is retrieved from third-party sources. The connections between the calculating engines and these external sources are made off-line, which indicates that the real-time update of the data is not supported.
7) Given that many people experience difficulty naming and distinguishing colours, the colour-coding scheme used for value visualization may create some confusion for the users.

5.4. Recommendations for Future Work

Based on the findings obtained during the testing and development of this research, along with the limitations presented previously, this research recommends the following points for further investigation:

1) Modelling the technical performance of various MEP systems that exist in a building and incorporating this performance as a metric to evaluate design has been proven to be successful. However, as this research is laying the foundation of such a practice, further

exploration for other models offered by reliability theory (e.g., maintenance model) is recommended. Furthermore, modelling level of details (i.e., considering the studied system as one system or as a set of connected sub-systems) is another aspect that should be explored in order to improve the result of the application of the MCLCA framework, where researchers can associate each level of assessment (e.g., preliminary, detailed, conceptual, etc.) with a level of details for performance modelling.

2) The MCLCA framework presented in this research provides the foundation for the development of a performative design engine, where the machine can assist designers to generate better-performing buildings at a lower cost and minimal environmental impact. Therefore, it is recommended to incorporate the mentioned framework with the practice of generative design to develop a performative design engine.
3) As mentioned earlier, a major limitation of this research is the manual work in declaring the interferences and developing the value model. Hence, it is recommended to utilize artificial intelligence techniques to assist practitioners to overcome the hassle of manual work.
4) Understanding the interdependencies among building systems and their collective performance during operation is a major aspect for the application of the MCLCA framework. Therefore, further investigating for the performance of systems and their interactions is recommended, whether using reliability theory or other techniques, as understanding such behaviour is important for the improved design of the systems.
5) The application of the MCLCA framework using criteria other than that used in this research is another avenue to be explored. Also, incorporating values of a qualitative nature

is an important improvement for this framework, and will considerably increase the benefit of utilization for more sustainable solutions.

BIBLIOGRAPHY

Abell, M., and Napier, J. (2014). "Effect of rigid diaphragms on buckling of a cruciform structure." https://wiki.csiamerica.com/display/kb/Effect+of+rigid+diaphragms+on+buckling+of+a+cruciform+structure.

Ackoff, R. L. (1989). "From data to wisdom." *Journal of Applied Systems Analysis,* 16(1), 3-9.

Akao, Y., and Mazur, G. H. (2003). "The leading edge in QFD: past, present and future." *International Journal of Quality & Reliability Management,* 20(1), 20-35.

Alberta Climate Leadership Plan. (2016). "Carbon pricing." http://www.alberta.ca/climate-carbon-pricing.cfm (04/03, 2016).

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2015). *2015 ASHRAE handbook : heating, ventilating, and air-conditioning applications.* Ashrae, Atlanta, Ga.

American Society of Tool and Manufacturing Engineers (ASTME). (1967). *Value engineering in manufacturing; a reference book on the theory, principles, application, and administration of value engineering and analysis in industry.* Prentice-Hall, Englewood Cliffs, N.J.

Ansari, S. L. (1997). *Target costing: the next frontier in strategic cost management.* Irwin Professional Publishing, Chicago.

Ansari, S., Bell, J., and Okano, H. (2006). "Target Costing: Uncharted Research Territory." *Handbooks of Management Accounting Research,* Elsevier Ltd, 507-530.

Anvari, A., Ismail, Y., and Hojjati, S. M. H. (2011). "A study on total quality management and lean manufacturing: through lean thinking approach." *World Applied Sciences Journal,* 12(9), 1585-1596.

Arroyo, P., Tommelein, I. D., and Ballard, G. (2015). "Comparing AHP and CBA as Decision Methods to Resolve the Choosing Problem in Detailed Design." *Journal of Construction Engineering and Management,* 141(1), 04014063.

Autodesk. (2017). "Change the Graphics Properties of a Material." https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2016/ENU/Revit-Customize/files/GUID-5DFA9F47-B6FF-4D79-A240-FA27BEA7C7AB-htm.html (September 13, 2017).

Ax, C., Greve, J., and Nilsson, U. (2008). "The impact of competition and uncertainty on the adoption of target costing." *International Journal of Production Economics,* 115(1), 92-103.

Azhar, S., Carlton, W. A., Olsen, D., & Ahmad, I. (2011). Building information modeling for sustainable design and LEED® rating analysis. *Automation in construction*, *20*(2), 217-224.

Ballard, G. (2012). "Target value design." *DS 70: Proceedings of DESIGN 2012, the 12th International Design Conference, Dubrovnik, Croatia*.

Ballard, G. (2008). "The lean project delivery system: An update." *Lean Construction Journal,* 2008 1-19.

Ballard, G. (2000). "The last planner system of production control". ProQuest Dissertations Publishing.

Ballard, G. (1999). "Improving work flow reliability." *Proceedings of the 7 the Annual Conference of the International Group for Lean Construction,* 275-286.

Ballard, G. (1993). "Lean Construction and EPC performance improvement." *1st Annual Conf. of the Int. Group for Lean Production*.

Ballard, G., and Pennanen, A. (2013). "Conceptual estimating and target costing." *Proceedings of the 21st Annual Conference of the International Group for Lean Construction (IGLC), Fortaleza, 31 July-2 August* 217-226.

Barkokebas, B. (2017). "BIM Implementation for Conventional On-Site and Off-Site Manufacturing Construction". University of Alberta.

Benjamin, N. B. (1969). "Competitive bidding for building construction contracts."

Berman, J., and Pfleeger, J. (1997). "Which industries are sensitive to business cycles." *Monthly Labor Review,* 120 19.

Bertoni, A., Bertoni, M., Massimo, P., Christian, J., and Tobias, L. (2015). "Expanding Value Driven Design to meet Lean Product Service Development." *Procedia CIRP*, *30*, 197-202.

Bertoni, M., Bertoni, A., Broeze, H., Dubourg, G., and Sandhurst, C. (2014). "Using 3D CAD Models for Value Visualization: An Approach with SIEMENS NX HD3D Visual Reporting." *Computer-Aided Design and Applications,* 11(3), 284-294.

Bertoni, M., Bertoni, A., Isaksson, O., Amnell, H., and Johansson, C. (2013). "Value-oriented concept selection in aero-engine sub-systems design: the EVOKE approach." *INCOSE,* Philadelphia.

Blischke, W. R., and Murthy, D. N. P. (2003). *Case studies in reliability and maintenance.* Wiley-Interscience, Hoboken, NJ.

Blokhin A. (2015). "What is the Utility Function and How is it Calculated?" https://www.investopedia.com/ask/answers/072915/what-utility-function-and-how-it-calculated.asp (Nov 13, 2017).

Bobzin, H. (2017). "History of Utility-based Theory." http://www.hagen-bobzin.de/mikro/nutzen-history.html (Nov 13, 2017).

Briggs, R. (2014). "Normative Theories of Rational Choice: Expected Utility." *The Stanford Encyclopedia of Philosophy,* E. N. Zalta, ed., Metaphysics Research Lab, Stanford University.

Bribián, I. Z., Usón, A. A., & Scarpellini, S. (2009). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment*, *44*(12), 2510-2520.

Bu Hamdan, S., Barkokebas, B., Alwisy, A., Bouferguene, A., and Al-Hussein, M. (2017). "Visual-based value assessment application in the construction industry." *In IABSE Symposium Report* (Vol. 108, No. 1, pp. 183-189). IABSE, Bath.

Build Carbon Neutral. (2007). "Estimate the embodied CO2 of a whole construction project." http://buildcarbonneutral.org/ (Jun 1, 2017).

Buyle, M., Braet, J., & Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews*, *26*, 379-388.

Campbell, R. A. (1863). *Popular Lectures and Addresses*.

Carron, T., and Lambert, P. (1994). "Color edge detector using jointly hue, saturation and intensity." *Image Processing, 1994. Proceedings. ICIP-94., IEEE International Conference,* IEEE, 977-981.

Castagne, S., Curran, R., Price, M., Collopy, P., Murphy, A., and Raghunathan, S. (2006). "Value driven design optimization of aircraft structures." *6TH AIAA Aviation Technology, Integration and Operations (ATIO) Forum, Wichita, Kansas, 25th-27th September 2006, 25th-27th September 2006*.

Chan, L. K., & Wu, M. L. (2002). Quality function deployment: A literature review. *European journal of operational research*, *143*(3), 463-497.

Chen, H. M. (2017). "An Overview of Information Visualization." *Library Technology Reports,* 53(3), 5.

Cheung, J., Scanlan, J., Wong, J., Forrester, J., Eres, H., Collopy, P., Hollingsworth, P., Wiseall, S., and Briceno, S. (2012). "Application of Value-Driven Design to Commercial AeroEngine Systems." *Journal of Aircraft,* 49(3), 688-702.

Chicksand, D., and Cox, A. (2005). "The Limits of Lean Management Thinking:: Multiple Retailers and Food and Farming Supply Chains." *European Management Journal,* 23(6), 648-662.

Chwe, M. S. (2013). *Rational ritual: Culture, Coordination, and Common Knowledge.* Princeton University Press.

Circular Ecology. (2011). "Embodied Energy and Embodied Carbon." http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html (Jun 1, 2017).

Collopy, P. D. (2012). "A research agenda for the coming renaissance in systems engineering." *50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition,* 799.

Collopy, P. D., and Hollingsworth, P. M. (2011). "Value-Driven Design." *Journal of Aircraft,* 48(3), 749-759.

Cooper, R., and Slagmulder, R. (1999). "Develop profitable new products with target costing." *Sloan Management Review,* 40(4), 23.

Curran, R. (2010). "Value-Driven Design and Operational Value." *Encyclopedia of Aerospace Engineering*.

Cusumano, M. A. (1994). "The Limits of "Lean"." *Sloan Management Review,* 35(4), 27.

De Melo, Reymard Savio Sampaio, Do, D., Tillmann, P., Ballard, G., and Granja, A. D. (2016). "Target Value Design in the public sector: Evidence from a hospital project in San Francisco, CA." *Architectural Engineering and Design Management,* 12(2), 125-137.

Dekker, H., and Smidt, P. (2003). "A survey of the adoption and use of target costing in Dutch firms." *International Journal of Production Economics,* 84(3), 293-305.

Delgado-Hernandez, D. J., Bampton, K. E., and Aspinwall, E. (2007). "Quality function deployment in construction." *Construction Management and Economics,* 25(6), 597-609.

Dell'Isola, A. J. (1982). *Value engineering in the construction industry.* Van Norstrand Reinhold Company, New York.

Dell'Isola, A. J. (1974). *Value Engineering in the Construction Industry.* Construction Publishing Company, New York.

Dell'Isola, A. J. (1966). "Value Engineering in Construction." *Civil Engineering,* 36(9), 58-61.

Dror, S. (2016). "Identify Important Factors for Service Simulation Experiments Using QFD." *Quality and Reliability Engineering International,* 32(6), 2107-2114.

Edwards, W. (2013). *Utility theories: Measurements and applications.* Springer Science & Business Media.

Ellram, L. M. (2006). "The Implementation of Target Costing in the United States: Theory Versus Practice." *Journal of Supply Chain Management,* 42(1), 13-26.

Emiliani, B., Kensington, C., and Most, U. S. (2005). "Lean in higher education." *Center for Lean Business Management. Available at Http://Www.Superfactory.Com/Articles/Lean_higher_ed.Aspx*.

European Space Agency. (2012). "What is concurrent engineering?" http://www.esa.int/Our_Activities/Space_Engineering_Technology/CDF/What_is_concurrent_engineering (Sep 11, 2017).

Everaert, P. (1999). "The impact of target costing on cost, quality and time-to-market of new products: results from lab experiments". Vanderbilt University.

Everaert, P., Loosveld, S., Van Acker, T., Schollier, M., and Sarens, G. (2006). "Characteristics of target costing: theoretical and field study perspectives." *Qualitative Research in Accounting & Management,* 3(3), 236-263.

Feil, P., Yook, K., and Kim, I. (2004). "Japanese target costing: a historical perspective." *International Journal,* 11.

Fekete, J., Van Wijk, J., Stasko, J., and North, C. (2008). "The value of information visualization." *Information Visualization,* 1-18.

Ferri, E., Buffiere, J., Ludwig, W., Gravouil, A., and Edwards, L. (2006). "Fatigue crack propagation: In situ visualization using X-ray microtomography and 3D simulation using the extended finite element method." *Acta Materialia,* 54(4), 1111-1122.

Fishburn, P. C. (1968). "Utility Theory." *Management Science,* 14(5), 335-378.

Fong, P. S. (2004). "A critical appraisal of recent advances and future directions in value management." *European Journal of Engineering Education,* 29(3), 377-388.

Fowler, T. C. (1990). *Value Analysis in Design.* Van Nostrand Reinhold, New York.

Gagne, M. L., and Discenza, R. (1995). "Target costing." *Journal of Business & Industrial Marketing,* 10(1), 16-22.

Gaweda, R. (2015). "RC Slab deflection." https://knowledge.autodesk.com/support/robot-structural-analysis-products/troubleshooting/caas/screencast/Main/Details/8acb3cdf-4226-41e2-aff2-c5e8ac8db26f.html (May 31, 2017).

Georgy, M. E., Chang, L., and Zhang, L. (2005). "Utility-function model for engineering performance assessment." *Journal of Construction Engineering and Management,* 131(5), 558-568.

Gerst, M., Eckert, C., Clarkson, J., and Lindemann, U. (2001). "Innovation in the tension of change and reuse." *International Conference on Engineering Design 01,* A2.

Gibson, R. B. (2006). "Beyond the pillars: sustainability assessment as a framework for effective integration of social, economic and ecological considerations in significant decision-making." *Journal of Environmental Assessment Policy Management,* 8(03), 259-280.

González, M. J., & Navarro, J. G. (2006). Assessment of the decrease of CO 2 emissions in the construction field through the selection of materials: practical case study of three houses of low environmental impact. *Building and Environment*, *41*(7), 902-909.

Govindan, K., Shankar, K. M., & Kannan, D. (2016). Sustainable material selection for construction industry–A hybrid multi criteria decision making approach. *Renewable and Sustainable Energy Reviews*, *55*, 1274-1288.

Guinee, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., and Rydberg, T. (2010). "Life cycle assessment: past, present, and future." *Environmemtal Science & Technology,* 45(1), 90-96.

Hansmann, R., Mieg, H. A., and Frischknecht, P. (2012). "Principal sustainability components: empirical analysis of synergies between the three pillars of sustainability." *International Journal of Sustainable Development & World Ecology,* 19(5), 451-459.

Hart, S. L. (1971). "Axiology-Theory of Values." *Philosophy and Phenomenological Research,* 32(1), 29-41.

Hauser, J. R., and Clausing, D. (1988). "The house of quality." *Harvard Business Review*, *Vol. 66*.

Hazelrigg, G. A. (1998). "A framework for decision-based engineering design." *Transactions-American Society of Mechanical Engineers Journal of Mechanical Design,* 120 653-658.

Helms, M. M., Ettkin, L. P., Baxter, J. T., and Gordon, M. W. (2005). "Managerial implications of target costing." *Competitiveness Review: An International Business Journal,* 15(1), 49-56.

Heydarian, A., and Golparvar-Fard, M. (2011). "A visual monitoring framework for integrated productivity and carbon footprint control of construction operations." *Computing in Civil Engineering,* 504-511.

Hopp, W. J., and Spearman, M. L. (2004). "To pull or not to pull: what is the question?" *Manufacturing & Service Operations Management,* 6(2), 133-148.

Horne, R., Grant, T., and Verghese, K. (2009). *Life cycle assessment : principles, practice, and prospects.* CSIRO Publishing, Collingwood, Vic.

Howell, G. A. (1999). "What is lean construction-1999." *Proceedings IGLC,* Citeseer, 1.

Howell, G. A., and Koskela, L. J. (2000). "Reforming project management: the role of lean construction." *Proceedings of the 8th Annual Conference of the International Group for Lean Construction*.

Hutcheon, N. B., and Handegord, G. O. (1983). *Building science for a cold climate.* Wiley.

Ibusuki, U., and Kaminski, P. C. (2007). "Product development process with focus on value engineering and target-costing: A case study in an automotive company." *International Journal of Production Economics,* 105(2), 459-474.

Isaksson, O., Kossmann, M., Bertoni, M., Eres, H., Monceaux, A., Bertoni, A., Wiseall, S., and Zhang, X. (2013). "Value-Driven Design–A methodology to link expectations to technical requirements in the extended enterprise." *INCOSE International Symposium,* Wiley Online Library, 803-819.

Isaksson, O., Larsson, T. C., and Rnnbck, A. h. (2009). "Development of product-service systems: challenges and opportunities for the manufacturing firm." *Journal of Engineering Design,* 20(4), 329-348.

ISO. (2006). "Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006)." International Organization for Standardization, Geneva.

ISO 8402. (1999). "Quality management and quality assurance - Vocabulary." International Organization for Standardization, Geneva.

Jackson, M. (2005). "Embodied energy and historic preservation: A needed reassessment." *Apt Bulletin,* 36(4), 47-52.

Jelodar, M. B., Yiu, T. W., and Wilkinson, S. (2014). "A Multi-Objective Decision Support System for Selecting Dispute Resolution Methods in the Construction Industry." *Computing in Civil and Building Engineering,* 1642-1649.

Jensen, P., Hamon, E., and Olofsson, T. (2009). "Product development through lean design and modularization principles." *Annual Conference of the International Group for Lean Construction: 13/07/2009-19/07/2009,* 465-474.

Jo, H. H., Parsaei, H. R., and Sullivan, W. G. (1993). "Principles of concurrent engineering." *Concurrent engineering,* Springer, 3-23.

Joblove, G. H., and Greenberg, D. (1978). "Color spaces for computer graphics." *ACM siggraph computer graphics,* ACM, 20-25.

Juster, F. T. (1990). "Rethinking utility theory." *Journal of Behavioral Economics,* 19(2), 155-179.

Kammerl, D., Schockenhoff, D., Hollauer, C., Weidmann, D., and Lindemann, U. (2017). "A Framework for Sustainable Product Development." *Sustainability Through Innovation in Product Life Cycle Design,* Springer, 21-32.

Kanakana, G. M. (2013). "Lean in service industry." *Southern African Institute of Industrial Engineering 2013*.

Kaplinski, O. (2010). "Risk analysis of construction projects: From risk identification to contingency timetable." *Advances and Trends in Structural Engineering, Mechanics and Computation,* 268.

Karlsson, M., and Norrman, A. (2010). "Product LifeCycle Visualization." *Visual Forum 2010: Unleash the Power of Viaualization; May 3; Norrkö ping; 2010,* Linkping University Electronic Press.

Kathawala, Y., and Motwani, J. (1994). "Implementing quality function deployment: a systems approach." *The TQM Magazine,* 6(6), 31-37.

Kato, Y. (1993). "Target costing support systems: lessons from leading Japanese companies." *Management Accounting Research,* 4(1), 33-47.

Katzner, D. W. (1970). "Static demand theory."

Kee, R. (2013). "Target costing in the presence of product and production interdependencies." *Advances in Management Accounting,* 22 135-158.

Kee, R. (2010). "The sufficiency of target costing for evaluating production-related decisions." *International Journal of Production Economics,* 126(2), 204-211.

Khoo, L. P., and Ho, N. C. (1996). "Framework of a fuzzy quality function deployment system." *International Journal of Production Research,* 34(2), 299-311.

Kim, Y., and Lee, H. W. (2010). "Analyzing user costs in a hospital: methodological implication of space syntax to support whole-life target value design." *Lean Construction Journal,* 11 55-63.

Knight, C. R. (1991). "Four decades of reliability progress." *Reliability and Maintainability Symposium, 1991. Proceedings., Annual,* IEEE, 156-160.

Korkmaz, S., Messner, J. I., Riley, D. R., and Magent, C. (2010). "High-performance green building design process modeling and integrated use of visualization tools." *Journal of Architecture Engineering,* 16(1), 37-45.

Koskela, L. (1997). "Lean production in construction." *Lean Construction,* 1-9.

Koskela, L. (1992). *Application of the new production philosophy to construction.* Stanford University Stanford, CA.

Kulathilake, K.A.S.H. (2015). "Color and Color Models [PowerPoint slides]" Retrieved from: https://www.slideshare.net/shkulathilake/color-and-color-models-43400611 (Nov 21, 2017).

Chan, L. and Wu, M. (2002). "Quality function deployment: a literature review." *European Journal of Operational Research,* 143(3), 465.

Leahy, T. (1998). "The Target Costing Bull's Eye, Part One of a Series." http://businessfinancemag.com/bpm/target-costing-bulls-eye-part-one-series (Mar 10, 2017).

Lean Construction Institute. (2016). "History." https://www.leanconstruction.org/about-us/what-is-lean-design-construction/history/ (Nov 21, 2017).

Ledley, R. S., Buas, M., and Golab, T. J. (1990). "Fundamentals of true-color image processing." *Pattern Recognition, 1990. Proceedings., 10th International Conference on,* IEEE, 791-795.

Levkowitz, H., and Herman, G. T. (1993). "GLHS: A generalized lightness, hue, and saturation color model." *CVGIP: Graphical Models and Image Processing,* 55(4), 271-285.

Li, M., Jin, L., and Wang, J. (2014). "A new MCDM method combining QFD with TOPSIS for knowledge management system selection from the user's perspective in intuitionistic fuzzy environment." *Applied Soft Computing,* 21 28-37.

Macomber, H., Howell, G., and Barberio, J. (2007). "Target-value design: Nine foundational practices for delivering surprising client value." *AIA Practice Management Digest*.

Maniak, R., Midler, C., Lenfle, S., and Pellec-Dairon, M. L. (2014). "Value Management for exploration projects." *Project Management Journal,* 45(4), 55-66.

Mazur, G. (2016). "History of QFD." http://www.qfdi.org/what_is_qfd/history_of_qfd.html (Feb 2, 2017).

Mazzocato, P., Savage, C., Brommels, M., Aronsson, H., and Thor, J. (2010). "Lean thinking in healthcare: a realist review of the literature." *Quality and Safety in Health Care,* 19(5), 376-382.

McGraw Hill Construction. (2013). "Lean Construction." McGraw Hill Construction, Bedford, MA, USA.

Memarzadeh, M., and Golparvar-Fard, M. (2012). "Monitoring and visualization of building construction embodied carbon footprint using DnAR-N-dimensional augmented reality models." *Construction Research Congress 2012: Construction Challenges in a Flat World,* 1330-1339.

Meyer, G. W., and Greenberg, D. P. (1980). "Perceptual color spaces for computer graphics." *ACM SIGGRAPH Computer Graphics,* 14(3), 254-261.

Miles, L. D. (1961). *Techniques of Value Analysis and Engineering.* McGraw-Hill, New York.

Mohamed, S., and McCowan, A. K. (2001). "Modelling project investment decisions under uncertainty using possibility theory." *International Journal of Project Management,* 19(4), 231-241.

Moses, F., and Stahl, B. (1979). "Reliability analysis format for offshore structures." *Journal of Petroleum Technology,* 31(03), 347-354.

Mudge, A. E. (1971). *Value Engineering: A Systematic Approach.* McGraw-Hill, New York.

National Economics and Development Authority (NEDA). (2009). *Value Analysis Handbook.* Australian Government - AusAID, Canberra, Australia.

Nawi, M. M., Jalaluddin, S., Zulhumadi, F., Ibrahim, J. A., and Baharum, F. (2014). "A strategy for improving construction projects sustainability through value management approach." *International Journal of Applied Engineering Research,* 9(24), 28377-28385.

Nenadl, J. (2016). "Adequacy, Suitability, Effectiveness and Efficiency of Quality Management Systems: How to perceive and assess them?" *Quality Innovation Prosperity,* 20(2), 39-52.

Nicolini, D., Tomkins, C., Holti, R., Oldman, A., and Smalley, M. (2000). "Can target costing and whole life costing be applied in the construction industry: evidence from two case studies." *British Journal of Management,* 11(4), 303-324.

NIST/SEMATECH e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898/handbook/eda/section3/eda366h.htm, (January 20, 2018).

Novak, V. M. (2012). "Value paradigm: Revealing synergy between lean and sustainability." *20th annual meeting of the International Group for Lean Construction, San Diego, CA*.

Obi, L. I., and Arif, M. (2015). "A case for Target Value Design towards effective low-cost housing project cost management and performance in south-east zone Nigeria." *CIB Proceedings 2015: Going North for Sustainability: Leveraging Knowledge and Innovation for Sustainable Construction and Development,* 104.

Ohno, T. (1988). *Toyota production system: beyond large-scale production.* crc Press.

Oliva, C. A., de Castro, F., Granja, A. D., and de Melo, Reymard Svio Sampaio. (2017). "Comparison of the design management process by simulation: traditional and Target Value Design." *PARC Research in Architecture and Building Construction,* 7(3), 170-177.

Owlia, M. S., and Aspinwall, E. M. (1998). "A framework for measuring quality in engineering education." *Total Quality Management,* 9(6), 501-518.

P2SL. (2017). "Target Value Design." http://p2sl.berkeley.edu/research/initiatives/target-value-design/ (March 10, 2017).

Parker, D. E. (1985). *Value Engineering Theory.* Lawrence D Miles Value Foundation.

Petroski, J. (2002). "Thermal challenges facing new-generation light-emitting diodes (LEDs) for lighting applications." *Solid state lighting II,* International Society for Optics and Photonics, 215-223.

Popova, A. (2015). "Ecotect." http://www.iaacblog.com/programs/ecotect-3/ (May 31, 2017).

Project Management Institute (PMI). (2013). *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)-Fifth Edition (ENGLISH).* Project Management Institute, Newtown Square, PA.

Public Buildings Service. (1992). "Value Engineering Program Guide for Design and Construction" *Report. No.1.*

Quiggin, J. (1982). "A theory of anticipated utility." *Journal of Economic Behavior & Organization,* 3(4), 323-343.

Rausand, M., and Arnljot, H. (2004). *System reliability theory: models, statistical methods, and applications.* John Wiley & Sons.

Ribeiro, I., Peças, P., Silva, A., & Henriques, E. (2008). Life cycle engineering methodology applied to material selection, a fender case study. *Journal of Cleaner Production*, *16*(17), 1887-1899.

Rischmoller, L., Alarcn, L. F., and Koskela, L. (2006). "Improving value generation in the design process of industrial projects using CAVT." *Journal of Management in Engineering,* 22(2), 52-60.

Russell-Smith, S. V., Lepech, M. D., Fruchter, R., and Meyer, Y. B. (2015). "Sustainable target value design: integrating life cycle assessment and target value design to improve building energy and environmental performance." *Journal of Cleaner Production,* 88 43-51.

Schroeder, M. (2016). "Value Theory." *The Stanford Encyclopedia of Philosophy,* E. N. Zalta, ed., Metaphysics Research Lab, Stanford University.

Schwartz, S. H. (2007). "Basic Human Values: Theory, Methods, and Applications." *Risorsa Uomo*.

Sharma, A., Saxena, A., Sethi, M., & Shree, V. (2011). Life cycle assessment of buildings: a review. *Renewable and Sustainable Energy Reviews*, *15*(1), 871-875

Serrano R., and Feldman, A. M. (2011). "Preferences and Utility." http://www.econ.brown.edu/Faculty/serrano/textbook/Lesson2.pdf (Nov 13, 2017).

Simon, H. A. (1996). *The sciences of the artificial.* MIT press.

Simon, H. A., and Larkin, J. H. (1987). "Why a diagram is (sometimes) worth 10,000 words." *Models of Thought,* 2.

Soban, D. S., Price, M. A., and Hollingsworth, P. (2012). "Defining a Aesearch Agenda in Value Driven Design: Questions That Need to be Asked." *Journal of Aerospace Operations,* 1(4), 329-342.

Spear, S., and Bowen, H. K. (1999). "Decoding the DNA of the Toyota production system." *Harvard Business Reviews,* 77 96-108.

Staats, B. R., Brunner, D. J., and Upton, D. M. (2011). "Lean principles, learning, and knowledge work." *Journal of Operations Management,* 29(5), 376-390.

Statistics Canada. (2012). "Greenhouse gas emissions, by sector." http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/envi42a-eng.htm (Apr 6, 2016).

Stigler, G. J. (1950a). "The development of utility theory. I." *Journal of Political Economy,* 58(4), 307-327.

Stigler, G. J. (1950b). "The development of utility theory. II." *Journal of Political Economy,* 58(5), 373-396.

Sugimori, Y., Kusunoki, K., Cho, F., and Uchikawa, S. (1977). "Toyota production system and kanban system materialization of just-in-time and respect-for-human system." *The International Journal of Production Research,* 15(6), 553-564.

Surendra, A., Ferraro, M., Schumann, B., Van Schaik, J., Daniels, J. J., Gorissen, D., Scanlan, J. P., and Keane, A. J. (2012). "The challenges of using Value-Driven Design for practical design of UAVs." *Journal of Aerospace Operations,* 1(4), 377-386.

Tao, R., and Tam, C. (2013). "System reliability theory based multiple-objective optimization model for construction projects." *Autom.Constr.,* 31 54-64.

Tao, R., and Tam, C. (2012). "System reliability optimization model for construction projects via system reliability theory." *Autom.Constr.,* 22 340-347.

The new York Times. (2017). "Auto & Truck Manufacturers Industry Snapshot." http://markets.on.nytimes.com/research/markets/usmarkets/industry.asp?industry=53111 (Mar 22, 2017).

Thoft-Christensen, P., and Murotsu, Y. (2012). *Application of structural systems reliability theory.* Springer Science & Business Media.

Turskis, Z., Gajzler, M., and Dziadosz, A. (2012). "Reliability, risk management, and contingency of construction processes and projects." *Journal of Civil Engineering and Management,* 18(2), 290-298.

U.S. Department of Defense. (1986). "Value Engineering." U.S. Department of Defense, Washington DC, USA.

U.S. Department of Defense. (1983). "Principles and Applications of Value Engineering." U.S. Department of Defence, Washington DC, USA.

U.S. Department of Transportation. (2015). "The Value Engineering (VE) Process and Job Plan." https://www.fhwa.dot.gov/ve/veproc.cfm (Mar 22, 2017).

U.S. Department of Transportation. (1997). "Value Engineering." Federal Highway Administration: Washington, DC.

Wang, M. Q., and Ma, Y. S. (2007). "A systematic method for mapping customer requirements to quality characteristics in product lifecycle." *International Journal of Simulation and Process Modelling,* 3(4), 229-237.

West Virginia Department of Transportation/ Division of Highways (WVDOH). (2004). "Value Engineering Manual." Charleston, WV: WVDOH Office Service Division.

Womack, J. P., and Jones, D. T. (2010). *Lean thinking: banish waste and create wealth in your corporation.* Simon and Schuster.

Womack, J. P., Jones, D. T., and Roos, D. (1990). *The Machine that changed the world.* Simon and Schuster.

Wong, J. K. W., & Kuan, K. L. (2014). Implementing 'BEAM Plus' for BIM-based sustainability analysis. *Automation in construction*, *44*, 163-175

Yang, Y. Q., Wang, S. Q., Dulaimi, M., and Low, S. P. (2003). "A fuzzy quality function deployment system for buildable design decision-makings." *Automation in construction,* 12(4), 381-393.

Zhang, X., Auriol, G., Eres, H., and Baron, C. (2013). "A prescriptive approach to qualify and quantify customer value for value-based requirements engineering." *International Journal of Computer Integrated Manufacturing,* 26(4), 327-345.

Zhuang, J., Hu, M., and Mousapour, F. (2017). "Value-Driven Design process: A systematic decision-making framework considering different attribute preferences from multiple stakeholders." *Journal of Solar Energy Engineering,* 139(2), 6.

Zimina, D., Ballard, G., and Pasquire, C. (2012). "Target value design: using collaboration and a lean approach to reduce construction cost." *Construction Management & Economics,* 30(5), 383-398.

APPENDIX A

Floor plans of the house used in Section 4.1.

Figures A.1, A.2, and A.3 present the floor plans of the basement, main floor, and second floor, respectively.

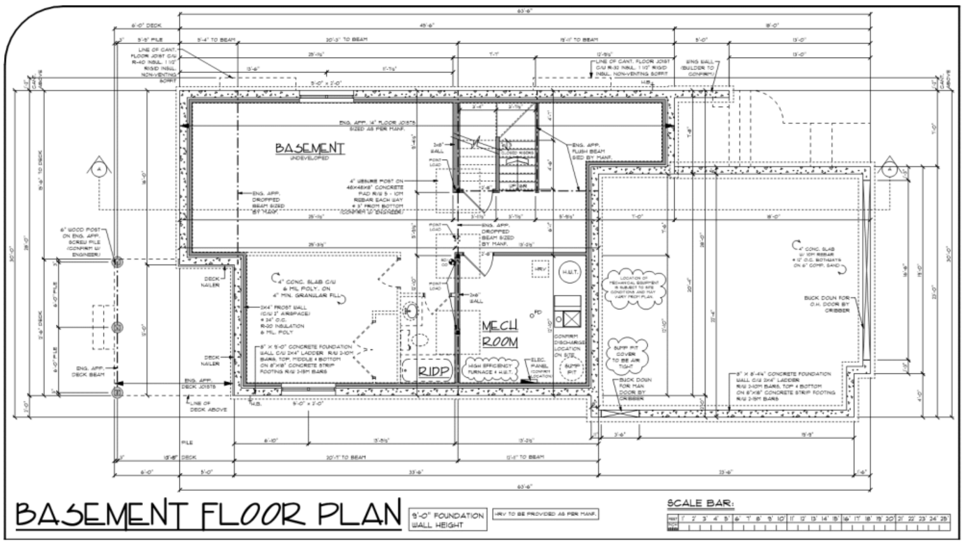


Figure 0A-01 Basement floor plan

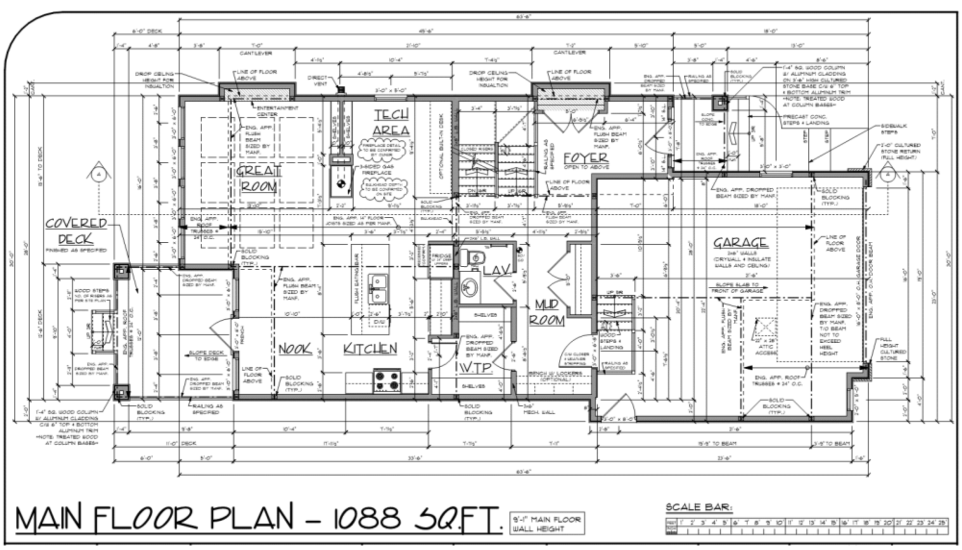


Figure 0-2 Main floor plan

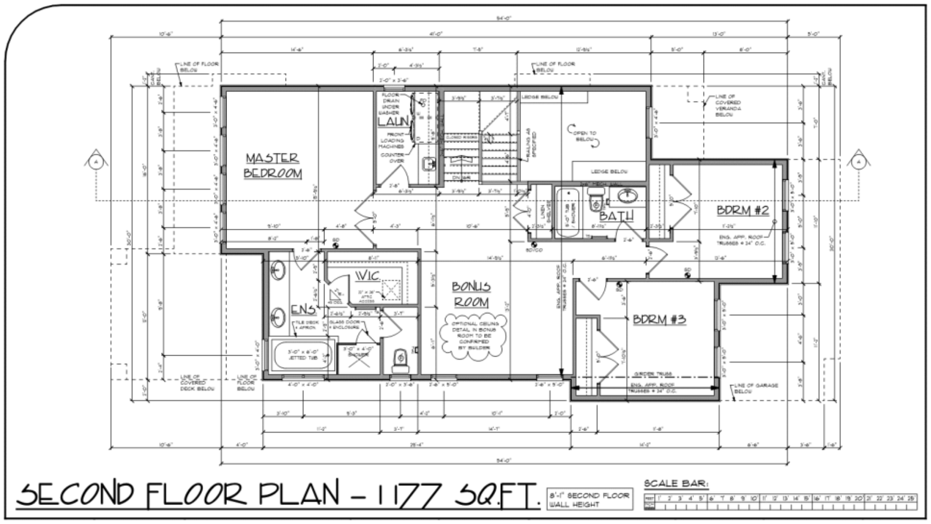


Figure A-3 Second floor plan

APPENDIX B

Technical specification of HVAC systems used in Section 4.1

- High Efficiency Heat Pump:
    - Efficient 12 SEER/7.7 HSPF (Heating Seasonal Performance Factor) < 11.25-ton split/packaged heat pump system
    - Forward curved constant volume fan and premium efficiency motor
    - 2.0 inch of water gauge (498 pascals) static pressure Constant Volume duct system
    - Integrated differential dry-bulb temperature economizer
    - Domestic hot water unit (0.575 Energy Factor)
- ASHRAE Heat Pump:
    - Efficient 14 SEER/8.3 HSPF (Heating Seasonal Performance Factor) <5.5-ton split/packaged heat pump system
    - Residential constant volume cycling fan
    - 2.0 inch of water gauge (498 pascals) static pressure Constant Volume duct system
    - Integrated differential dry-bulb temperature economizer
    - Domestic hot water unit (0.575 Energy Factor)
- High Efficiency Package System:
    - Efficient 12 SEER, 90% AFUE furnace split system with gas heat
    - Forward curved constant volume fan and premium efficiency motor
    - 2.0 inch of water gauge (498 pascals) static pressure Constant Volume duct system
    - Integrated differential dry-bulb temperature economizer
    - Domestic hot water unit (0.575 Energy Factor)
- ASHRAE VAV:

- Water cooled centrifugal chiller (COP 5.96)
- Open, atmospheric pressure cooling tower with variable speed fan and 5°F (2.8°C) approach
- Forward curved fan with Variable Speed Drive (VSD) and premium efficiency motor
- 3.5 inch of water gauge (871.8 pascals) static pressure Variable Air Volume (VAV) duct system
- Integrated differential dry-bulb temperature economizer
- Resistance reheat boxes
- Variable volume chilled water pump
- Chilled water coil
- Variable volume condenser water pump
- Domestic hot water unit (0.575 Energy Factor)

- High Efficiency VAV:
    - Water cooled centrifugal chiller (COP 5.96)
    - Open, atmospheric pressure cooling tower with variable speed fan and 5°F (2.8°C) approach
    - Forward curved fan with Variable Speed Drive (VSD) and premium efficiency motor
    - 3.5 inch of water gauge (871.8 pascals) static pressure Variable Air Volume (VAV) duct system
    - Integrated differential dry-bulb temperature economizer

- Gas-fired hot water boiler with draft fan >2,500 kBtuh, 84.5% combustion efficiency
- Variable volume hot water pump
- Hot water coil
- Hot water reheat boxes
- Variable volume chilled water pump
- Chilled water coil
- Variable volume condenser water pump
- Domestic hot water unit (0.575 Energy Factor)

- ASHRAE Package Terminal:
  - 12 SEER/8.3 HSPF (Heating Seasonal Performance Factor) packaged terminal heat pump (PTHP)
  - Forward curved constant volume fan and premium efficiency motor
  - 0.25 inch of water gauge (62.3 pascals) static pressure Constant Volume duct system
  - Domestic hot water unit (0.575 Energy Factor)
- High Efficiency Package Terminal AC:
  - Packaged Variable Air Volume (PVAV) system with under floor air distribution
  - Forward curved fan with Variable Speed Drive (VSD) and premium efficiency motor
  - 3.5 inch of water gauge (871.8 pascals) static pressure VAV duct system
  - Gas-fired hot water boiler with draft fan >2,500 kBtuh, 84.5% combustion efficiency

- Integrated differential dry-bulb temperature economizer
- Variable volume hot water pump
- Hot water coil
- Hot water reheat boxes
- Improved efficiency domestic hot water heater (85% thermal efficiency)

APPENDIX C

Cost estimation details for the house used in Section 4.1.

Phase	Description	Item No.	BASEMENT	MAIN FLOOR	SECOND FLOOR	Unit of Measure	Unit Cost (CA$)	Total Amount (CA$)
A-BS	**Basement**							
	C.I.P. concrete forms, footing, spread, plywood, 4-use, includes erecting, bracing, stripping and cleaning	031113455150	430.67	0.00	0.00	SFCA	4.51	1,942.31
	C.I.P. concrete forms, footing, continuous wall, dowel supports, 1 use, includes erecting and bracing	031113450500	215.33	0.00	0.00	L.F.	4.11	885.02
	C.I.P. concrete forms, pile cap, square or rectangular, plywood, 4-use, includes erecting, bracing, stripping and cleaning	031113453150	48.00	0.00	0.00	SFCA	5.01	240.48
	C.I.P. concrete forms, wall, radial, smooth curved, below grade, job built plywood, to 8' high, 4 use, includes erecting, bracing, stripping and cleaning	031113854230	3,588.23	0.00	0.00	SFCA	11.34	40,690.48
	Structural concrete, ready mix, heavyweight, 4500 psi, includes local aggregate, sand, Portland cement (Type I) and water, delivered, excludes all additives and treatments	033113350350	88.08	0.00	0.00	C.Y.	205.57	18,106.31
	Structural concrete, placing, continuous footing, shallow, pumped, includes leveling (strike off) & consolidation, excludes material	033113701950	17.24	0.00	0.00	C.Y.	26.54	457.67
	Structural concrete, placing, caps, pumped, under 5 CY, includes leveling (strike off) & consolidation, excludes material	033113703750	2.88	0.00	0.00	C.Y.	36.16	104.14

	Structural concrete, placing, slab on grade, pumped, up to 6" thick, includes leveling (strike off) & consolidation, excludes material	033113704350	20.11	0.00	0.00	C.Y.	30.89	621.30
	Structural concrete, placing, walls, pumped, 8" thick, includes leveling (strike off) & consolidation, excludes material	033113704950	47.84	0.00	0.00	C.Y.	39.84	1,905.98
A-FL	**Flooring**							
	Wood framing, composite wood joists, 11-1/2" deep	061110183010				M.L.F.	2939.07	0.00
	Sub floor 23/32” T&G O.S.B. – glued and screwed	061623100205	0.00	1,025.57	1,194.11	SF Flr.	1.52	3,373.91
	Carpet – 100% nylon cut pile or Berber with 7# underlay.	096816100720	0.00	0.00	795.45	S.Y.	39.95	31,778.28
	Hardwood	096429100020	0.00	722.20	0.00	S.F.	4.81	3,473.78
	Tile	093213107000	0.00	175.67	246.72	S.F.	1.26	532.21
A-WE	**Exterior walls**							
	Wall framing, studs, 2" x 6", 8' high wall, pneumatic nailed	061110406165	0.00	1.33	1.01	M.B.F.	1,340.29	3,136.11
	Wall framing, walls, for second story and above, add	061110406165	0.00	0.00	1.01	M.B.F.	1,340.29	1,352.35
	Vapor retarders, building paper, polyethylene vapor barrier, standard, 2 ml (.002" thick)	072610100600	0.00	1,730.14	1,177.66	Sq.	13.17	38,295.67
	Blanket insulation, for walls or ceilings, kraft faced fiberglass, 6" thick, R21, 23" wide	072113100580	0.00	1,730.14	1,177.66	S.F.	1.37	3,983.68
	Gypsum wallboard, on walls, fire resistant, taped & finished (level 4 finish), 5/8" thick	092910302150	0.00	1,730.14	1,177.66	S.F.	1.28	3,721.98
	Paints & coatings, walls & ceilings, interior, concrete, drywall or plaster, latex paint, primer or sealer coat, smooth finish, brushwork	099123720200	0.00	1,730.14	1,177.66	S.F.	0.39	1,134.04
A-WI	**Interior walls**							

	Wall framing, studs, 2" x 6", 8' high wall, pneumatic nailed	061110406165	0.00	0.11	0.01	M.B.F.	1,340.29	164.86
	Wall framing, walls, for second story and above, add	061110406165	0.00	0.00	0.01	M.B.F.	1,340.29	16.08
	Wall framing, studs, 2" x 4", 8' high wall, pneumatic nailed	061110406145	0.00	0.49	1.02	M.B.F.	1,384.55	2096.61
	Wall framing, walls, for second story and above, add	061110406145	0.00	0.00	1.02	M.B.F.	1,384.55	1,416.11
	Gypsum wallboard, on walls, fire resistant, taped & finished (level 4 finish), 5/8" thick	092910302150	0.00	1,257.04	1,861.58	S.F.	1.28	3,991.83
	Paints & coatings, walls & ceilings, interior, concrete, drywall or plaster, latex paint, primer or sealer coat, smooth finish, brushwork	099123720200	0.00	1,257.04	1,861.58	S.F.	0.39	1,216.26
A-WF	**Frost walls**							
	Wall framing, studs, 2" x 4", 8' high wall, pneumatic nailed	061110406145	0.85	0.00	0.00	M.B.F.	1,384.55	1,172.71
	Vapor retarders, building paper, polyethylene vapor barrier, standard, 2 ml (.002" thick)	072610100600	1,162.81	0.00	0.00	Sq.	13.17	15,314.14
	Blanket insulation, for walls or ceilings, kraft faced fiberglass, 6" thick, R21, 23" wide	072113100580	1,162.81	0.00	0.00	S.F.	1.37	1,593.04
	Gypsum wallboard, on walls, fire resistant, taped & finished (level 4 finish), 5/8" thick	092910302150	1,162.81	0.00	0.00	S.F.	1.28	1,488.39
A-CE	**False ceiling**							
	Double 2 x 6 rim board, nailed & Double 2 x 6 rim plate on flat with Etafoam		0.00	116.66	116.66	Ea. (16')	6.06	1,413.95
	Ceiling joist 2 x 6 @ 16" o/c				29.00	Ea. (16')	6.06	
	Blown in Cellulose fiber insulation, 5 1/2", c/w retainer net	IN25200	0.00	11.66	90.00	Bag	10.32	1,049.13
	1x3 strapping @ 16" o/c	LU12120			27.00	Ea. (12')	4.33	
	Double 5/8" Fire code drywall, screwed (moisture resistant in bathroom)	LU12821	0.00	3.33	6.49	Sheet	13.62	133.71

A-FI	**Interior finish**							
	Hardboard paneling, moldings for, wood grained MDF	062513102100	0.00	386.65	495.10	L.F.	1.96	1,728.22
A-WD	**Windows***							
	5x2		2.00	0.00	0.00	Ea.	444.58	889.16
	2x5		0.00	1.00	0.00	Ea.	411.35	411.35
	3x3		0.00	1.00	0.00	Ea.	340.69	340.69
	3x5		0.00	1.00	4.00	Ea.	698.60	3,493.00
	3x6		0.00	6.00	0.00	Ea.	481.31	2,887.86
	2x3.5		0.00	0.00	2.00	Ea.	399.84	799.68
	2.5x5		0.00	0.00	2.00	Ea.	149.34	298.68
	3x4.5		0.00	0.00	5.00	Ea.	375.15	1,875.75
	3x4		0.00	0.00	1.00	Ea.	313.42	313.42
	4x4		0.00	0.00	1.00	Ea.	641.79	641.79
A-DO	**Doors**							
	2'-4"		0.00	1.00	0.00	Ea.	139.80	139.80
	2'-6"	081416090140	0.00	2.00	6.00	Ea.	139.80	1,118.40
	2'-8'		2.00	0.00	1.00	Ea.	229.43	688.29
	3' x 6'-8"	081416090380	0.00	1.00	0.00	Ea.	229.43	229.43
	Weather Stripping	087125101100	0.00	1.00	0.00	Opng.	225.48	225.48
	4' (closet)	081433203240	0.00	0.00	1.00	Opng.	297.05	297.05
	5' (closet)	081433203260	0.00	2.00	2.00	Opng.	328.14	1,312.56
	5' (Double Fold)		0.00	0.00	1.00	Ea.	301.97	301.97
	Grage Door		1.00	0.00	0.00	Ea.	3,728.05	3,728.05
A-KI	**Kitchen**							
	Custom cabinets, rule of thumb: kitchen cabinets, excl. counters & appliances, maximum	112223109600	0.00	8.00	1.00	L.F.	663.46	5,971.14
	Kitchen sink Double Stainless Steel (Under mount) with single lever chrome faucet		0.00	1.00	0.00	Ea.	1,187.36	1,187.36
A-BA	**Bathroom**							

	Lavatory, vanity top, vitreous china, white, round, single bowl, 19", includes trim	224116133020	0.00	1.00	3.00	Ea.	392.16	1,568.64
	Faucets/fittings, lavatory faucet, center set with single control lever handle, polished chrome, with pop-up drain	224139102290	0.00	1.00	3.00	Ea.	328.84	1,315.36
	Toilet (Wall Hung Two piece, close coupled)	224113130400	0.00	1.00	2.00	Ea.	730.07	2,190.21
	Shower		0.00	0.00	1.00	Ea.	275.93	275.93
	Tub		0.00	0.00	2.00	Ea.	16,336.88	32,673.76
	Mirrors, wall type, polished edge, 1/4" plate glass, over 5 SF, excl. frames	088313100200	0.00	0.00	24.00	S.F.	16.15	387.60
	Medicine cabinets, with mirror, stainless steel frame, unlighted, 16" x 22"	102816200020	0.00	1.00	1.00	Ea.	196.63	393.26
	Subtotal							189,532.74
	Miscellaneous materials							18,953.27
A-PL	Plumbing				1.00	Lump	75,813.09	75,813.09
A-SP	Sprinklers				1.00	Lump	9,476.64	9,476.64
A-EL	Electrical, heating & ventilation				1.00	Lump	142,149.55	142,149.55
	Total Cost							435,925.295

APPENDIX D

Changes in C_{ops} due to changes in *WWR*, *SH*, and *WT*

Table D-1 Changes in C_{ops} due to changes in *WWR, SH,* and *WT*

Façade	Window type	Shade amount	Governing function
South	Single	1/3	$\Delta C_{ops_{S-WWR}} = -0.026 * S - WWR^2 - 1.78 * S - WWR - 14.89$
	Single	2/3	$\Delta C_{ops_{S-WWR}} = -0.017 * S - WWR^2 - 2.55 * S - WWR - 24.6$
	Double	1/3	$\Delta C_{ops_{S-WWR}} = -0.028 * S - WWR^2 - 6.11 * S - WWR - 23.31$
	Triple	1/3	$\Delta C_{ops_{S-WWR}} = -0.01 * S - WWR^2 - 2.23 * S - WWR - 7$
	Triple	2/3	$\Delta C_{ops_{S-WWR}} = 0.011 * S - WWR^2 - 6.34 * S - WWR + 180.05$
East	Single	1/3	$\Delta C_{ops_{E-WWR}} = 0.001 * E - WWR^2 - 11.83 * E - WWR + 59.9$
	Single	2/3	$\Delta C_{ops_{E-WWR}} = 0.0015 * E - WWR^2 - 12.25 * E - WWR + 57.57$
	Double	1/3	$\Delta C_{ops_{E-WWR}} = -0.002 * E - WWR^2 - 5.48 * E - WWR + 53.87$
	Double	2/3	$\Delta C_{ops_{E-WWR}} = -0.0011 * E - WWR^2 - 5.9 * E - WWR + 52.57$
	Triple	1/3	$\Delta C_{ops_{E-WWR}} = 0.003 * E - WWR^2 - 1.98 * E - WWR + 38.95$
	Triple	2/3	$\Delta C_{ops_{E-WWR}} = 0.0026 * E - WWR^2 - 2.2 * E - WWR + 36.84$
North	Single	1/3	$\Delta C_{ops_{N-WWR}} = 0.0041 * N - WWR^2 - 13.47 * N - WWR - 5.22$
	Single	2/3	$\Delta C_{ops_{N-WWR}} = 0.0037 * N - WWR^2 - 13.52 * N - WWR - 5.71$
	Double	1/3	$\Delta C_{ops_{N-WWR}} = 0.011 * N - WWR^2 - 22.81 * N - WWR - 5.07$
	Double	2/3	$\Delta C_{ops_{N-WWR}} = 0.011 * N - WWR^2 - 22.89 * N - WWR - 4.93$
	Triple	1/3	$\Delta C_{ops_{N-WWR}} = 0.003 * N - WWR^2 - 11.59 * N - WWR - 5.4$
	Triple	2/3	$\Delta C_{ops_{N-WWR}} = 0.003 * N - WWR^2 - 11.62 * N - WWR - 6.34$
West	Single	1/3	$\Delta C_{ops_{W-WWR}} = 0.0012 * W - WWR^2 - 12.33 * W - WWR + 75.44$
	Single	2/3	$\Delta C_{ops_{W-WWR}} = 0.004 * W - WWR^2 - 12.77 * W - WWR + 75.29$
	Double	1/3	$\Delta C_{ops_{W-WWR}} = 0.0015 * W - WWR^2 - 5.93 * W - WWR + 69.48$
	Double	2/3	$\Delta C_{ops_{W-WWR}} = 0.0003 * W - WWR^2 - 6.28 * W - WWR + 68.38$
	Triple	1/3	$\Delta C_{ops_{W-WWR}} = 0.0022 * W - WWR^2 - 2.11 * W - WWR + 45.52$
	Triple	2/3	$\Delta C_{ops_{W-WWR}} = 0.0027 * W - WWR^2 - 2.31 * W - WWR + 43.29$

APPENDIX E

Changes in EC_{ops} due to changes in *WWR*, *SH*, and *WT*

Table E-1 Changes in EC_{ops} due to changes in *WWR, SH,* and *WT*

Façade	Window type	Shade amount	Governing function
South	Single	1/3	$\Delta CE_{ops_{S-WWR}} = -0.36 * S - WWR^2 - 73.63 * S - WWR - 65.75$
	Single	2/3	$\Delta CE_{ops_{S-WWR}} = -0.2 * S - WWR^2 - 72 * S - WWR - 274.76$
	Double	2/3	$\Delta CE_{ops_{S-WWR}} = -0.11 * S - WWR^2 - 141.76 * S - WWR - 159.16$
	Triple	1/3	$\Delta CE_{ops_{S-WWR}} = -0.11 * S - WWR^2 - 141.76 * S - WWR - 159.16$
	Triple	2/3	$\Delta CE_{ops_{S-WWR}} = -0.32 * S - WWR^2 - 49.6 * S - WWR - 446.76$
East	Single	1/3	$\Delta CE_{ops_{E-WWR}} = 0.03 * E - WWR^2 - 159.8 * E - WWR + 1087.4$
	Single	2/3	$\Delta CE_{ops_{E-WWR}} = 0.05 * E - WWR^2 - 161.11 * E - WWR + 1081.9$
	Double	1/3	$\Delta CE_{ops_{E-WWR}} = 0.015 * E - WWR^2 - 82.55 * E - WWR + 1023.9$
	Double	2/3	$\Delta CE_{ops_{E-WWR}} = 0.015 * E - WWR^2 - 85.07 * E - WWR + 1043.3$
	Triple	1/3	$\Delta CE_{ops_{E-WWR}} = 0.037 * E - WWR^2 - 37.29 * E - WWR + 911.52$
	Triple	2/3	$\Delta CE_{ops_{E-WWR}} = 0.047 * E - WWR^2 - 38.52 * E - WWR + 916.88$
North	Single	1/3	$\Delta CE_{ops_{N-WWR}} = 0.05 * N - WWR^2 - 157.49 * N - WWR - 18.68$
	Single	2/3	$\Delta CE_{ops_{N-WWR}} = 0.048 * N - WWR^2 - 157.21 * N - WWR - 24.25$
	Double	1/3	$\Delta CE_{ops_{N-WWR}} = 0.14 * N - WWR^2 - 266.8 * N - WWR - 33.9$
	Double	2/3	$\Delta CE_{ops_{N-WWR}} = 0.141 * N - WWR^2 - 266.96 * N - WWR - 30.48$
	Triple	1/3	$\Delta CE_{ops_{N-WWR}} = 0.041 * N - WWR^2 - 136.6 * N - WWR - 18.87$
	Triple	2/3	$\Delta CE_{ops_{N-WWR}} = 0.038 * N - WWR^2 - 136.16 * N - WWR - 32.65$
West	Single	1/3	$\Delta CE_{ops_{W-WWR}} = 0.061 * W - WWR^2 - 168.24 * W - WWR - 1600.2$
	Single	2/3	$\Delta CE_{ops_{W-WWR}} = 0.14 * W - WWR^2 - 173.84 * W - WWR - 1716.2$
	Double	1/3	$\Delta CE_{ops_{W-WWR}} = 0.028 * W - WWR^2 - 92.23 * W - WWR - 1585.8$
	Double	2/3	$\Delta CE_{ops_{W-WWR}} = 0.088 * W - WWR^2 - 95.3 * W - WWR - 1646.6$
	Triple	1/3	$\Delta CE_{ops_{W-WWR}} = 0.03 * W - WWR^2 - 39.66 * W - WWR + 1303$
	Triple	2/3	$\Delta CE_{ops_{W-WWR}} = 0.044 * W - WWR^2 - 39.3 * W - WWR + 1268.3$