BIM-Based Decision Support for Evaluation of Architectural Submittals during Construction

by

Ibraheem N. Albukhari

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Civil Engineering

Waterloo, Ontario, Canada, 2014

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Submittal review is a formal process that takes place after construction has begun. All materials, equipment, and processes submitted by a contractor are evaluated for compliance with specifications before they can be installed in a project. For projects that involve unique architectural features, contractors often submit alternatives that entail minor deviations from some of the specifications. To save project time and avoid the acceptance of faulty items that can have a costly long-term impact on the project, thorough assessment is necessary. To improve the evaluation process, this research has developed a structured BIM-based decision support framework. The proposed framework does not reject submittals with minor deviations; rather, it determines the value of accepting them if they conform to the original design rationale and also meet acceptance thresholds for technical criteria. Additional construction and operational costs associated with acceptance of the submittals are also calculated; the contractor must cover/absorb these costs as a condition of acceptance. All approved submittals are then updated in a Building Information Model and recorded in a submittal log for tracking and verification purposes.

For this research, windows were identified as key architectural submittals for high-profile buildings. To facilitate their evaluation, BIM is used for modeling and storing design rationale and specification data, which are then utilized by the proposed decision support system. The system evaluates the extent to which the window submittals comply with design rationale criteria, applies multi-attribute utility theory (MAUT) and the analytical hierarchy process (AHP) to assess compliance with performance-related criteria, and also computes the overall utility of a submittal and its related life cycle cost. BIM integration with the decision support tool results in the efficient automation of the submittal evaluation process, thus saving time and reducing subjectivity. Storing the design rationale and performance-related criteria in the BIM also enables specifications to be dynamically updated with the data from the approved submittals, thereby facilitating enhanced building operation. The integrated framework has been validated through a case study and is expected to help project managers make efficient, minimally subjective decisions that include consideration of long-term impact and the best value for a project.

Acknowledgements

I thank ALLAH, the most Gracious and the most Merciful, for giving me the will and strength to complete this work.

I wish to express my deep gratitude to my supervisor, Prof. Tarek Hegazy, for his sincere guidance, extensive assistance, critical insight, and patience without which I would not have been able to complete this work. It has been a great honor to work with and learn from him.

I am very grateful to the Saudi Cultural Bureau in Ottawa, which represents the Saudi Arabian Ministry of Higher Education and to Umm Al-Qura University for facilitating my study in Canada and for providing financial support throughout my PhD program.

I would like to thank my committee members for their insightful comments:

Prof. Carl Haas, Prof. Adil Al-Mayah, and Prof. Frank Safayeni.

I would also like to thank **Prof. John Straube** for his valuable guidance and assistance.

Furthermore, I want to thank my colleagues in the construction research group for their invaluable friendship, for all the wonderful times we shared, and for providing the friendly environment that made work such a pleasure.

I also would like to express sincere appreciation to my parents for their pray, emotional support, and encouragement throughout the period of my studies.

I owe a debt of gratitude to my wife, for her love, support, and dedication. I am also in debt to my children, for the time I spent away from them studying and researching.

To

*My **P**arents,*

*my **W**ife, and*

*my **K**ids*

Table of Contents

List of Figures

List of Tables

Nomenclature

ACH	Air Change per hour [1/hr]
AHP	Analytical Hierarchy Process
BIM	Building Information Modeling
Btu	British Thermal Unit
CDDs	Cooling Degree-Days [$^{\circ}$C-day]
cfm	Cubic feet per minute
CIDDs	Cooling Infiltration Degree-Days
C_p	Heat Capacity of Air [0.284 Wh/Kg-K]
E	Energy Consumption [Kwh]
HDDs	Heating Degree-Days [$^{\circ}$C-day]
HIDDs	Heating Infiltration Degree-Days
MAUT	Multi-Attribute Utility Theory
Q	Heat Loss [W]
UA	Envelope Conductivity or Thermal Conductivity [W/K]
U-Value	Heat transfer coefficient [$W/m^2.^{\circ}K$]
ρ	Density of air [1.2 kg/m^3]

Chapter 1

Introduction

1.1 Background

Building design is a process that involves continual selection, organization, and analysis of the elements that generate a final product. The final design represents a convenient combination of several disciplines that embody the decisions and intentions of architects and engineers (Liescheidt 2003). The design stage is, in fact, a major step in the life cycle of a project and has a significant impact on both cost and performance, as shown in Figure 1-1 (Hegazy 2002). The contractor, who is the party responsible for constructing the proposed design, is expected to meet the levels of performance and quality as indicated and documented in the drawings and specifications for the project (Liescheidt 2003; Rosen et al. 2010).

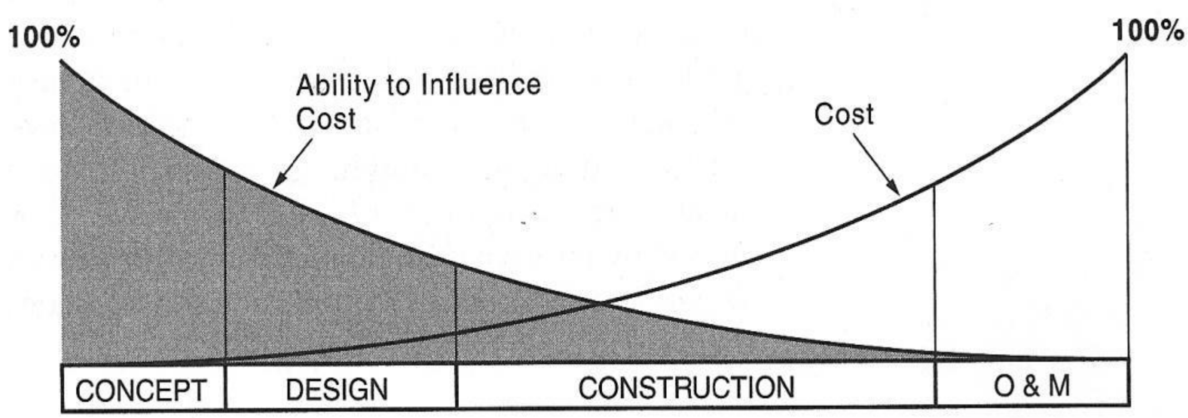


Figure 1-1: Impact of Design on the Life Cycle Cost of a Building (Hegazy 2002)

These drawings and specifications that are generated during the design stage have an enormous impact on the construction and operation stages of building projects, as is clearly apparent in the study reported by Josephson and Hammarlund (1999). They discovered that approximately 30 % of all defects developed during construction activities and that approximately 55 % of all defects that appeared during the operation and maintenance phases were due to design defects. Although both drawings and specifications are intrinsic components of the construction process, specifications have greater legal priority than drawings (CI 2007; Rosen et al. 2010) and are, in fact, often a primary source of construction disputes (Jahren and Dammeier 1990).

In an effort to accelerate the preparation of specifications, requirements for the final design may be provided based on experience, previous specifications, generic standards, and inadequate detail (Emmitt 2001). The net effect of less detailed specifications, however, may be to transfer problems and disputes forward to the construction phase (Kululanga and Price 2005) and to open the door to changes and modifications to the original design and specifications. The final as-built specifications for many building components and their actual operational characteristics are therefore updated and finalized during the actual construction (Sherbini 2010). Toole and Hallowell (2005) listed 24 building components whose specifications were not determined until after construction had begun.

Contracts require that, during construction, the contractor follow a formal review process, called submittal review, before they can use a specific type of material or product on the project. This deliberate and essential process (De Lapp 2003) is important to “demonstrate … the way by which the contractor proposes to conform to the information given and the design concept expressed in the Contract Documents” (AIA 2007). Throughout the submittal review process, the general contractor must submit samples and/or shop drawings of all proposed materials, equipment, and products, according to an approved submittal schedule (Porter 2008). The evaluation and approval of these submittals can be difficult due to time constraints (typically 14 days), information missing from the submittal package (Atkins and Simpson 2006; Liescheidt 2003), and problems related to the retrieval of related information from differing file formats (Wood 1996). In addition, the lack of defined criteria for the evaluation can exacerbate these difficulties (Sherbini 2010), especially when minor changes or deviations can affect overall performance and have implications for the construction and operation of the project. Personnel who have limited experience or who have recently graduated may be assigned to evaluate the submittals (Elovitz 2003; Garrett and Lee 2010), which can affect the quality of the associated evaluation decisions.

1.2 Research Motivation

The goal of the research presented in this thesis was to develop a BIM-based decision support framework to be used for the evaluation of architectural submittals during construction. The motivation for the research is explained in the following subsections.

1.2.1 Importance of Architectural Submittals

As reported by Sherbini (2010), architectural submittals constitute about 25 % of all construction submittals and also involve significant amounts of materials and products. Architectural components are unique in that aesthetic requirements entail the inclusion of subjective factors in their evaluation (e.g., colour level, style, texture, etc.) so that, in practice, subjectivity, intuition, and experience are major factors in the evaluation of architectural submittals.

Architectural components must also exhibit sufficiently sound technical performance to prevent undue heat gain or loss through the weakest thermal bridge in buildings: windows. The energy consumed in order to compensate for such undesirable heat transfer cost the United States $20 billion in 1990 alone (one-fourth of all the energy used for space heating and cooling) (Ander 2010). Another example of problems created by an architectural element is air leakage (Lstiburek 2001). Conditioned indoor air leaves through openings in the building enclosure while hotter or cooler outdoor air enters, an undesirable exchange that occurs because windows represent a common source of air leakage.

Windows also absorb, reflect, and emit solar radiation (CSBR 2007; Lstiburek 2001). In residential buildings, careful window design and specifications can significantly reduce energy consumption: from 10 % to 50 % below the accepted practice in most climates (Ander 2010). The efficient evaluation and selection of windows, including during the submittal review process, can save energy, reduce loads on other systems, and enhance indoor air quality.

1.2.2 Need to Document Design Rationale

The evaluation of submittals that involve minor deviations from the specifications can be extremely complex because, in traditional practice, the original rationale is undocumented, even for well-organized designs (Hegazy et al. 2001). Preventing any violation of the original design intent requires a full understanding of the rationale behind the original design. Such detailed design information, as expressed in the design rationale, can be a key factor in the acceptance of one item over another during submittal evaluation, especially for architectural components that involve non-measurable features such as aesthetics. For example, for consistency with the desired architectural and aesthetic features, the designers may suggest that the windows be white aluminum frame with double blue-tinted glazing. Documentation of such a design rationale makes it possible to determine the level of compliance of the actual window being submitted. An undocumented design rationale thus compounds the difficulties associated with the evaluation of architectural submittals.

1.2.3 Benefits of Building Information Modeling

Building Information Modeling (BIM) is an emerging technology and process that promises to change the linear method of designing, analyzing, constructing, and managing buildings. BIM is an object-based parametric design tool (Eastman et al. 2011) that uses 3-D objects to create all architectural elements, such as walls, floors, columns, and doors. BIM also produces representations of other building systems such as structural, mechanical, and plumbing. The objects are connected to a central database that contains all data related to the geometry and spatial relationships of all building components as well as associated functional information (e.g., manufacturer, material, and cost) (Birx 2005; Sabol 2007; Goedert and Meadati 2008). For doors and windows, all drawings can be generated consistently from the 3-D model along with the quantities of materials and the relevant scheduling details. In this research BIM was adopted as a means of ensuring the development of a coordinated and integrated framework for storing and updating construction documents throughout the life cycle of a facility.

Regardless of the mechanism for evaluating submittal options, updating the specifications and drawings remains a manual (linear) process, which is slow and error prone (Hardin 2009). The 3D BIM model and its database depository therefore offer significant potential with respect to the automation of the as-built specification updates for use during the operation stage of the project.

1.2.4 Need for Practical Decision Support for Submittal Evaluation

Evaluating submittals is difficult, time consuming, and costly and involves numerous levels of engineers and administrators (Kilper 2002; Wood 1996). Minor specification changes can often lead to substantial expense or even loss of life. Elovitz (2002), for example, related the case of an architect who was sued for approving submittals that changed the steel landing pads in a stairway from 10-gauge to 14-gauge, which caused the stairway to collapse, injuring two people. Another example involves windows that appear to be efficient during the construction stage but that consume extra energy or require additional maintenance during operation. The possibility of underestimating the impact of the change in the specification is relatively great, especially in the face of persistent pressure to accelerate the construction process. In addition, a lack of clear approval criteria can force reviewers to make on-the-spot decisions based only on subjective judgment, experience, and short-term goals. Some contractors deliberately use improper submittals in order to buy time. The likelihood of error is therefore high, and optimal decisions are far from assured. Practical decision support is thus needed so that appropriate evaluation criteria can be defined and an effective decision support methodology can provide a quantitative assessment of submittals. A thorough and automated submittal evaluation process ensures the contractor's understanding of and compliance with well-documented specifications, and also affords the opportunity to correct any omissions or errors. An automated process also enables the contractor to evaluate items before making a formal submission, thus saving both time and money.

1.3 Research Scope and Objectives

The primary objective of this research was to develop a BIM-based decision support framework to help decision makers evaluate architectural submittals during construction in an accurate, efficient, and speedy manner that includes consideration of the impact of construction-related and operation-related costs. The following were the main objectives of the work:

- Study existing processes for the review of submittals related to architectural components and collect data to identify the most critical elements that significantly impact the performance and operation of a facility and therefore require special attention during the submittal review process.

- Define the design rationale and performance-related criteria related to the architectural components identified and develop a mechanism for storing the design rationale within a BIM system.

- Assess the construction-related and operation-related implications associated with the selected architectural components.

- Develop a BIM-based decision support framework that utilizes both the analytical hierarchy process (AHP) and multi-attribute utility theory (MAUT) for determining the best submittal proposed.

- Develop a prototype decision support system and validate its performance and benefits through a number of case studies.

1.4 Research Methodology

As illustrated in Figure 1-2, the methodology followed for the achievement of the above objectives can be summarized as follows:

1. Conduct an extensive literature review, and collect data related to past submittal packages from a variety of organizations in order to identify the most frequently occurring architectural submittals.

2. Establish the evaluation criteria for the top choice of the identified critical architectural submittals, including design rationale and performance-related criteria.

3. Identify and assess the associated construction and operation-related implications.

4. Using AHP and MAUT, develop a decision support tool that encompasses all critical items, evaluation criteria, weights, utility functions, thresholds, and calculation methods.

5. Establish and customize the BIM platform.

6. Integrate the BIM platform into the decision support tool in order to facilitate the development of the BIM-based decision support framework for the evaluation of architectural submittals.

7. Develop a prototype of the proposed framework.

8. Validate the prototype using case studies as a means of demonstrating its functionality and usefulness.

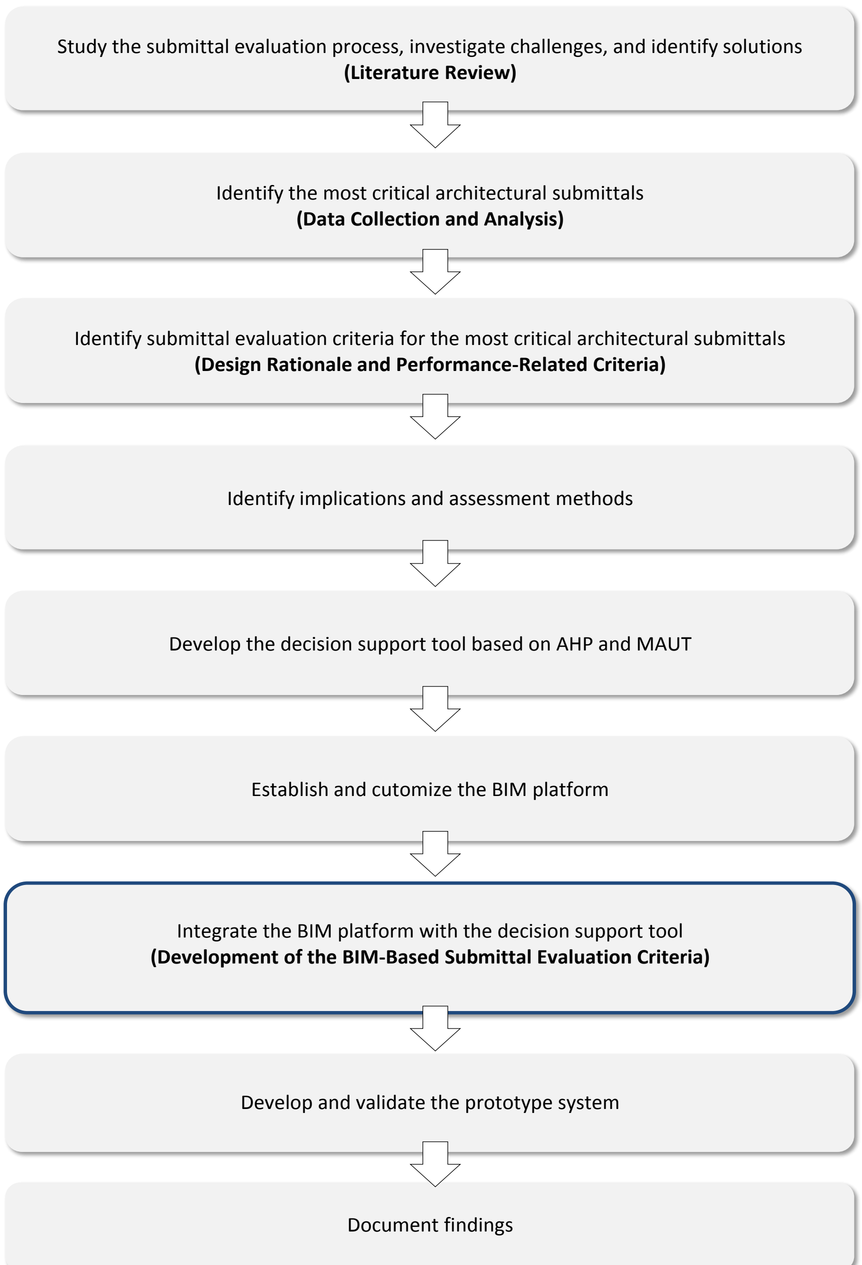


Figure 1-2: Research Methodology

1.5 Thesis Organization

The thesis is organized as follows:

Chapter 1 introduces the submittal evaluation process, the challenges associated with architectural submittals, the research motivation, the research scope and objectives, and the research methodology.

Chapter 2 provides a review of the existing research related to the submittal process, the associated challenges, and existing tools for managing submittals. Architectural building components are then addressed, and the challenges inherent in design documentation are discussed, including those related to specifications, drawings, and the documentation of the design rationale. Building Information Modeling (BIM) is presented as a promising platform for the visualization, communication, and management of project data. This chapter also explores the multi-criteria decision analysis (MCDA) techniques that can enhance decision support with respect to the submittal process.

Chapter 3 describes the process used for collecting data from numerous sources, for analyzing the data, and for identifying critical architectural submittals in order to select the top choice. Evaluation criteria for windows are listed, and aesthetics-related criteria are discussed.

Chapter 4 details the process of categorizing the evaluation criteria for windows, including a listing of two types of evaluation criteria: design rationale and performance-related criteria. Performance-related criteria are explained fully because of their effect on the overall performance of the building.

Chapter 5 introduces the conceptual approach for the development of the BIM-based decision support framework. An in-depth account of the workflow of the evaluation process is provided, including the phases, mechanism, and all related steps in the proposed framework. The chapter also describes the creation of a prototype system and its implementation in a hypothetical case study as a means of evaluating the effectiveness of the system.

Chapter 6 presents the validation and sensitivity analysis of the overall system based on a close-to-real-life case study.

Chapter 7 summarizes the research, including comments about its implementation; highlights its contributions; and presents recommendations for future work.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents a detailed literature review of the components of the research, including existing submittal problems, attempts at solutions, and the existing tools for managing submittals. Building components and documenting design rationale of Building Information Modeling (BIM) as a promising technology in the construction industry is introduced and presented in terms of applications and tools. The chapter then examines the Multi-Criteria Decision Analysis (MCDA) tools needed to improve evaluation and decision support for submittals.

2.2 Contract Documents

Construction is a complex and dynamic industry. A construction project involves activities and components that are huge in number and interrelated in nature. Building design is the very first step in the construction of a building, and during this phase the Architect/Engineer is responsible for developing the information necessary for the construction of a facility. This information is recorded in two types of documents: Contract Drawings and Contract Specifications (Rosen et al. 2010). These two types of documents, which are known as Contract Documents, represent a means of communicating information between the Architect/Engineer and the Contractor. However, each type uses a unique form of communication: the drawings are graphical depictions while the specifications are textual descriptions of the desired end result of the Work to be performed. In spite of these distinctions, the Contract Documents should be complementary and contain no contradictions or duplications.

2.3 Submittals

The accuracy of specification as source of information is critical, especially when specifications are rough. Despite efforts to optimize material selection decisions during the design phase, enhance the quality of the specifications, and clarify the design rationale, reviewing product or item data prior to fabrication or installation is always essential. This reviewing process exists for the purposes of conformance to the information and objectives provided in the specifications. Such a review is conducted through the submittal of detailed information about the product or item so that the owner (or his representative) can make an informed, wise decision about the adequacy of the item in question (Hinze 2010). Although submittals are not part of Contract Documents, they must be provided by the contractor during construction (Atkins and Simpson 2005).

According to the procedures governing contractor quality control (CQC), the contractor is responsible for performing the work in accordance with the Contract Documents. Conformance is demonstrated when the contractor presents a submittal prior to installation, which is then reviewed by a design professional who checks the detailed specifications for the materials or equipment submitted. During the review process, the design professional must ensure that the item submitted meets the grasp of design (Wyatt 2006) and the required performance parameters identified in the specification (East 2007; Liescheidt 2003). The significance of the submittal, in addition to its role as a quality control process (East 2007; Poles 1995), is that it is the final opportunity for the design professional to correct any mistakes in the design or to avoid any shortages. However, submittals review does not authorize design professionals to apply changes to the work (Liescheidt 2003; Schinnerer 2003).

With respect to operation and maintenance (O&M), submittals of the testing, adjusting, and balancing (TAB) report are considered a new reference value for the commissioning and testing procedure. As a result, modification may be required before the project is turned over to the operation team

(Turkaslan-Bulbul and Akin 2006). Fabricated items or other items requiring choices of the user can easily generate multiple submittals, depending on the complexity and details involved. In 2007, East stated that up to 11 different types of submittals were in general use in the construction industry, as listed in Table 2-1 (East 2007).

Table 2-1: Submittal Types (East 2007)

	Submittal Types
01	Preconstruction Submittals
02	Shop Drawings
03	Product Data
04	Samples
05	Design Data
06	Test Reports
07	Certificates
08	Manufacturer's Instructions
09	Manufacturer's Field Reports
10	Operation and Maintenance
11	Closeout Submittals

2.3.1 Submittal Procedure/Process

The American Institute of Architects (AIA), the Engineers Joint Contract Documents Committee (EJCDC), and the Associated General Contractors of America (AGC) mandate that a submittal process be provided and that requirements be within general project conditions. The process and requirements should be clearly defined in order to effectively regulate the timely flow of submittals (AIA 2007; William 1997; NAVFAC 2006).

To initiate the submittal process, a designer should identify and transfer a list of building components to be submitted, procured, and installed during construction. This list is referred to as a submittal log or register (NAVFAC 2006; East 2007). The submittal register should then be integrated with the contractor's critical path activities as approved by the consultant. The tracking of submittals during construction is accomplished through the use of the submittal register, in which all related activities, dates of submission, and recipients are recorded (Schinnerer 2003; NAVFAC 2006; Poles 1995; East 2007).

Each submittal proceeds in a loop from the contractor to the owner for approval, and then back to the contractor for procurement and execution (Mead 2001). Initiating the submittal is the responsibility of the general contractor; it is prepared either by the general contractor or by the subcontractor, supplier, or manufacturer involved. Once the product or component data is ready for consultant reviewing, it is attached to a transmittal form, called a submittal form. The submittal form contains a record of the project's reference information and subsequently the consultant's decision, at which point the transmittal form becomes a critical element in the entire process (Atkins and Simpson 2006; McGreevy 2002; NAVFAC 2009; Mead 2001).

The consultant decides whether the submitted product information is satisfactory or not. This process concludes when the consultant determines that the submittal falls into one of five categories: "approved", "approved as noted", "approved as noted resubmitting is required", "disapproved", or "no action" (McGreevy 2002). The submittal is then handed on to the contractor, who follows up on the decision through procurement or resubmission (Mead 2001). In short, the submittal process is time consuming yet critical to project performance.

Developing an efficient submittal evaluation process would result in better use of administrative time and enhance the efforts of all parties. Such a process would limit errors during the design and bidding phases while documenting all installed materials, equipment, and systems. According to Wyatt (1997), an efficient submittal evaluation process can be established through six steps: (1) thoughtfully edit the submittal requirement; (2) state the submittal requirement in understandable language; (3) publish a master list of the submittals required for the firm's projects; (4) improve record keeping; (5) reject improper submittals; and (6) promptly route, receive, and return submittals. These steps would result in a practical submittal evaluation process that increases the productivity of all parties and facilitates the likelihood of a successful project.

2.3.2 Challenges with Submittals

When considered as a process, management and review of submittals is an overwhelming and risky aspect of a project’s construction phase involving numerous activities (Ingold 2010; Atkins and Simpson 2006). Typical problems associated with this process include late submittals, incomplete submittals, submittals that do not comply with specifications, and missing submittals (Ingold 2010; Schinnerer 2003). Such problems interrupt the flow of construction and may lead to construction delays (Atkins and Simpson 2006), which can therefore result in late completion, loss of productivity, and cost increases (Atkins and Simpson 2006). Table 2-2 indicates several difficulties associated with submittals and solutions suggested by the literature (Sherbini 2010).

To overcome the problem of evaluating submittals, Sherbini (2010) developed a value-based decision support system that supports the evaluation of construction submittals. The proposed system was applied to a mechanical item: chiller. Multi-attribute Utility Theory (MAUT) was utilized to efficiently determine the best-value condition for approving a submittal considering its construction, operational, and LEED requirements. The validation of the system has demonstrated numerous benefits, including expedited decision process, more consistent and objective decisions, information for negotiation, and improved lifecycle asset performance.

Table 2-2: Submittal Problems and Solution Suggested in the Literature (Sherbini 2010)

Reference	Submittal Problem	Solution Suggested in the literature
Friedlander 2000; Atkins 2006	Inadequate submittal time in contract	Set fixed review time (14-19 days).
Ingold 2010; Atkins2006; Rickert 2002	Late submittals/ procrastination	Notify contractor to follow schedule.
Ingold 2010; Atkins2006	Forced substituton in submittals within a limited time	Reject submittal/request enough processing time.
Atkins 2006	Perform non approved work	Write to contractor that it is required by contract.
Ingold 2010; Atkins 2006	No submittal schedule	Suspend submittal until schedule is provided.
Schinnerer 2003	Deviation from schedule	No solution suggested.
Wyatt 1997	Lengthy process	Minimize number of items that require submittals.
wyatt 1997	Quality process not maintained	Give enough time to reviewer and have multiple reviewers.
Elovitz 2002	Inefficient decision	Provide detailed information and shop drawings.
Schinnerer 2003	submittal that is not required	No solution suggested.
Wyatt 1997	Undefined process	Review process in pre-construction conference.
Wood 1997; Schinnerer2003; piccolo2007	Inadequate information/Incompleteness/Lack of preparation	Insist to have contractor "reviewed" stamp before submitting submittals.
friedlander 2000	What is approved when submittal is "Approved"	Use another phrase like "no exceptions".
Rickert 2002	Submittals are trivial	Eliminate by appropriate specifications.
Rickert 2002	Over delegation	Expert awareness of importance of review.
RIckert 2002	Lack of support owner	Disapproved should be based on specification and owner preferences.
Kilper 2002	Lack of compliance with documents	No solution suggested.
Kilper 2002	Lack ofcoordination with related submittals	No solution suggested.
Piccolo 2007	Project delays	Give reviewers the needed information.
Wyatt 1997	Improper record of submittal	No solution suggested.
Ingold 2010; Schinnerer 2003; Frieddlander2000	Submittal not reviewed by contractor	No solution suggested.

2.3.3 Existing Tools for Managing Submittals

Managing submittals is a critical task that can overwhelm a construction team (Ingold 2010). Once submittals are received from the contractor, they need to be tracked with respect to receiving time, who received them, and to whom they have been forwarded for review. Traditionally, managing submittals involves three components. First, a spreadsheet is used to record and track each submittal (submittal register), with each new submittal requiring extensive data entry work. Files can have up to 10,000 pieces of unlinked information that must be entered manually. MS Word™, as the second component, is used for manually filed transmittal forms and to save important information separately from the spreadsheet. Filing these submittals as unlinked hardcopy or digital files represents an additional task for the construction team. The third component is the correspondence pertaining to submittal tasks such as letters, e-mails, or minutes of meetings (Rice and Haug 2007).

Increasing effort to control submittals has become apparent in the industry. Several computerized systems are available independently or as part of construction document management systems. The major submittal systems found in the literature are summarized in terms of their features and capabilities in Table 2-3.

Computerized submittal systems manage a submittal register by automatically tracking each submittal and thereby replacing the extensive labour required for data entry, follow-up, and note writing on scanned images or snapshots from CAD or/and BIM models. However, such systems lack decision support for submittal evaluation that considers compliance issues and construction and operation implications.

Table 2-3: Major Submittal Systems

Tools	Description
SUBMIT (Travakoli 1990)	A computer system for managing and storing active and non-active sbmittals. Facilitates follow-up by producing reports such as listing jobs, supplier submittals, past due submittals, and closeout reports.
(Furman et al. 2005)	An internet-based system and method for generating submittal packages using an expert logic engine.
(Rockey 2005)	An Electronic submittal system that involving linear levels of review, centralizing communication on the internet, and categorizing reviewers at each level in order to control the linear process.
(Harris 2006)	A submittal management tool that is based on networking all the material specifications from professionals and suppliers.
Submittal Exchange™ (Ostanik 2007)	A construction administration tool to manage all construction communication including submittals. Review and evaluation is done as annotations on an electronic copy of the submittal.
Construction Communicator™ (Construction Communicator 2009)	An online software program that digitally submits and receives submittals. All data are stored in main server for further tracking status and retrieving details.
BuildSite™ (BuildSite 2009)	An online system that automates submittal preparation during construction and reduces time for submittal preparation.
Virtual Construction™ (VICO 2010)	An online software that generates submittals based on the embedded data of Building Information Model (BIM).
AccuBuild™ (AccuBuild 2009)	A project management module that is able to find and track submittal information on submittal logs.
SpecsIntact™ (NASA 2010)	An automated system developed by National Aeronautics and Space administration (NASA) for creating design specifications; and exchanging, tracking, and reviewing submittal information.
Attolist™ (Attolist 2011; Khemlani 2009)	A comprehensive collaboration solution for all project parties to enhance document management and automate project work flow. All documents, including submittals and BIM models, are stored in a centralized and remoted Web server.
Newforma Project Center™ (Newforam 2011; Rice and Haug 2007; Khemlani 2011d)	A software that centralizes submittal tasks in one system where tracking and retrieving information is possible as well as gnerating output reports. Review and evaluation of shop drawings can be captured from BIM files. It helps in checking design changes and tracing of information through the enhanced collaboration mechanism. Not a web-based solution.

2.4 Architectural Components of Buildings

A building generally consists of a collection of spaces bounded by a set of spatial separators. Interior environments are divided by specific separators and are isolated from exterior environments by specially designed separators. The latter separators, collectively, constitute the building enclosure (Straube 2006). Figure 2-1 illustrates the components of building enclosure.

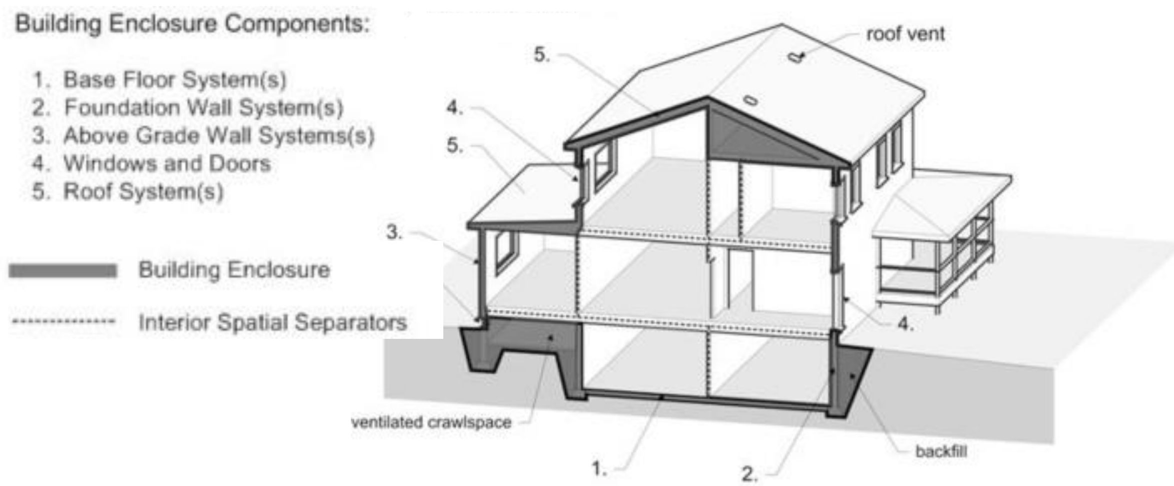


Figure 2-1: The Components of Building Enclosure (Straube 2006)

As indicated in Figure 2.1, a typical building enclosure usually consists of the roof system(s), the above-grade wall system(s) including windows (fenestration) and doors, the foundation wall system(s), and the base floor system(s) (Straube 2006). These systems constitute the major architectural components of a building enclosure. Architectural components involve a significant amount of material and products as well as a high sheer number of manufacturers and vendors. Architectural products and works of a building are described in 13 divisions (from divisions 02 through 14) in the *MasterFormat 2004* (Bunzick 2007) (Figure 2-2).

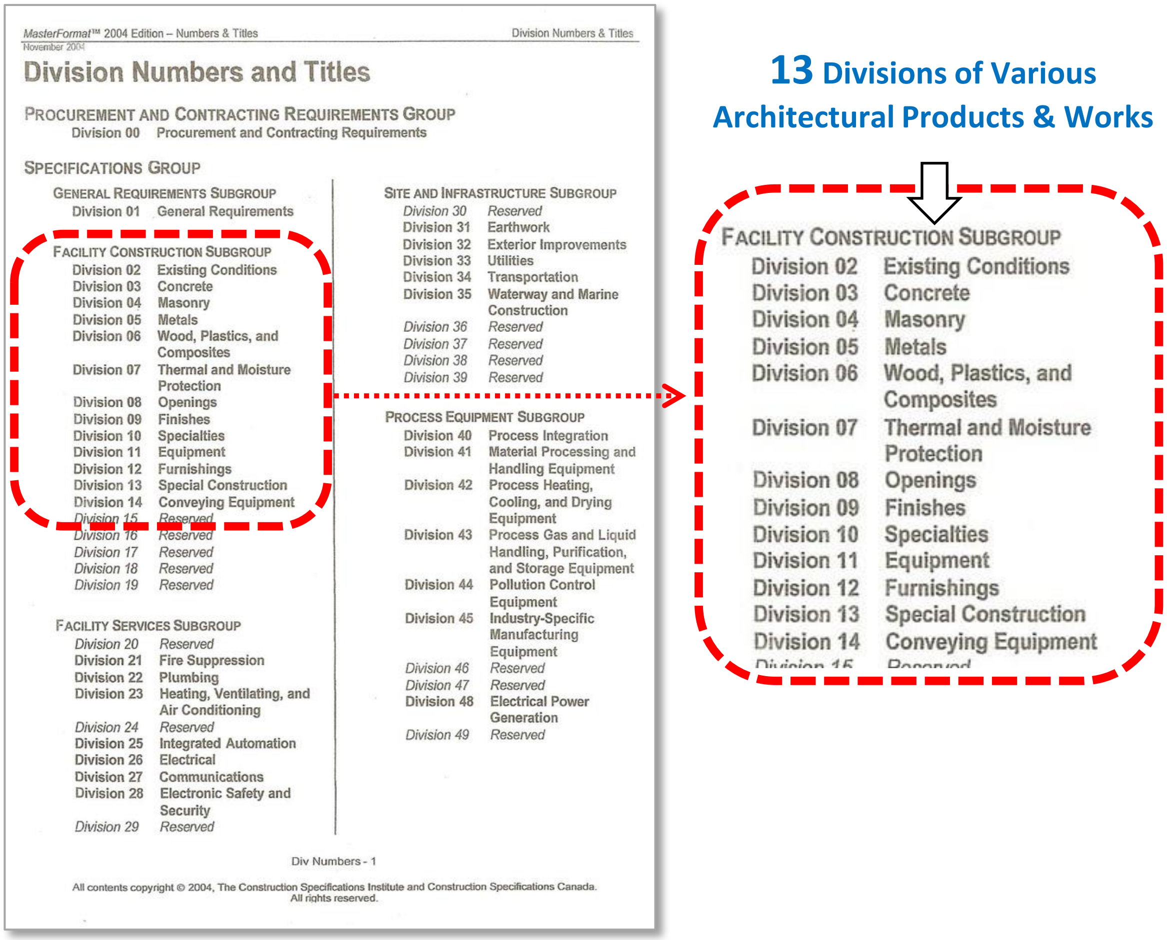


Figure 2-2: Specification *MasterFormat 2004* (CSI and CSC 2004)

As illustrated in Figure 2.2, examples of architectural works include Division 04 Masonry, Division 07 Thermal and Moisture Protection, Division 08 Openings (i.e. doors, windows, and skylights), and Division 09 Finishes.

Architectural components are critical for any building enclosure. Leak, a major concern in the buildings of today, is caused by the architectural component of windows (Olson et al. 2009; Lstiburek 2001). Whether the leakage is water or air, the problem remains significant. While water leakage can cause severe damage to building structure, air leakage can cause energy waste and discomfort. Ander

(2010) stated that energy consumed to compensate unwanted heat loss or gain through windows of residential and commercial buildings has cost the United States $20 billion in 1990 alone, which is equal to one-fourth of all the energy used for space heating and cooling. Ander mentioned that careful design and specifications of windows in residential buildings can reduce energy consumption significantly: from 10 to 50% below accepted practice in most climates (Ander 2010). The United States department of Energy (DOE) has concluded that up to 40% of the energy consumed to heat or cool a building is due to air leakage into and out of building (Fennell and Haehnel 2005).

Besides the criticality of architectural components, some components play an aesthetical role in addition to their functional role, such as components specified under “Division 09 Finishes”. Decision makers may face linguistic terms when evaluating such components; therefore, a structured analysis tool is needed to efficiently consider both qualitative and quantitative criteria.

2.5 Challenges in Design Documentation

The information necessary for construction of a facility is developed by the Architect/Engineer and is presented in two basic types of documents: Contract Drawings and Contract Specifications. Documenting design rationale is another critical issue. Each has its challenges that will be discussed in the following subsection.

2.5.1 Challenges Related to Specifications

The challenge of overcoming specification deficiencies has received great attention by focusing on enhancing writing methods, generating specifications, and checking the quality of specifications. Deficiencies in specification writing may lead to unnecessary dispute. Kululanga and Price (2005) have therefore explored the principles of writing construction specifications and the need for developing a methodology for evaluating the performance of this unique type of writing. Generating specifications that are consistent with drawings is the primary reason behind introducing automation of specifications. An online software program, called e-SPEC, has been introduced commercially for automating the preparation, checking, and updating of specifications (Figure 2-3). Integrated with a Building Information Model (BIM), e-SPECS links the BIM-based building components with master specifications, and simultaneously generates specifications while generating the 3D-model of the project on the BIM environment. In addition, information can be linked to the specifications of suppliers and manufacturer to enhance the practicality of the software (InterSpec 2007).

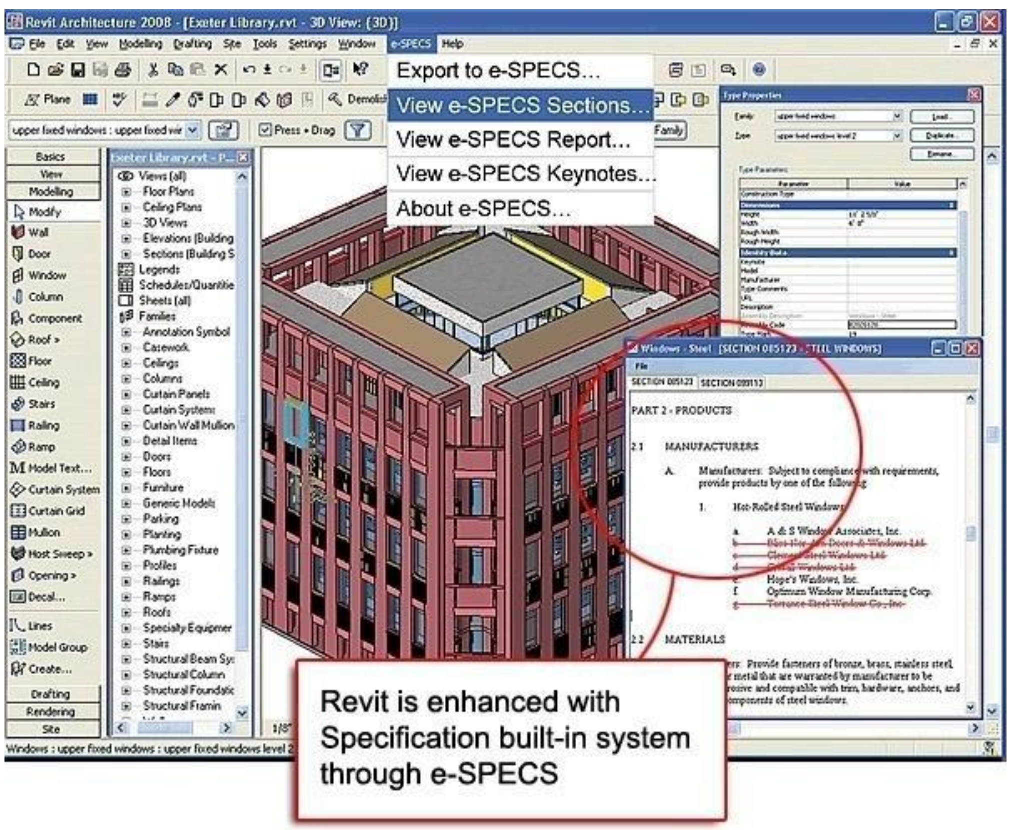


Figure 2-3: e-SPEC Linked to BIM Software

Compliance with building codes is another issue requiring automation in specifications. Horvat (2005) used the Extended Building Code (EBC) to evaluate the performance of a light-frame building envelope using MS Excel. The design stage assessment followed an established scoring system based on the requirements of the 1998 National Housing Code of Canada, which was used as a benchmark for the study (Horvat, 2005). In 2007, the EBC proposed a new framework utilizing decision tables to integrate code checking and performance analysis for a building envelop. This framework compared specifications with the building codes through the use of decision tables. Specifications either passed or failed according to a rules package (Tan et al. 2007). In Singapore, an e-plan checking project was conducted in the field of automated checking in construction. The e-plan checking project, known as the Construction Real Estate Network (CORENET), allowed Architecture/Engineering/Construction (AEC) professionals to submit project plans and documents online for review (Khemlani 2005). CORENET, as a comprehensive network system, was based on the checking of CAD drawings and developed to highly integrate four major building project life cycle processes: design, procurement, construction, and facilities management (Sing and Zhong 2001; Khemlani 2005).

2.5.2 Challenges Related to Drawings

The development of computers and electronic communications has changed the production of drawings. Economical and sophisticated equipment, programs, and software systems are available and in general use throughout the industry. Drawings have been generated using computer-aided design (CAD) software systems, such as AutoCAD (Autodesk, Inc.), Microstation (Bentley Systems Inc.), and Eaglepoint (Eagle Point). CAD, in general, is a 2D technology outputting a collection of victor lines and text that are accumulated to generate plans, elevations, sections, and details of a building (Demchak et al. 2009). Areas and lengths of vertical, horizontal, and curved lines can be measured precisely via CAD software system. Even though CAD has its efficiencies and advantages over pen and paper, its capabilities are limited in the context of complex construction projects and their needs, especially regarding information retrieval and management. CAD simply represents the geometric properties of the building entities (Holness 2006).

Traditionally, CAD system generates documents that are not correlated or intelligent-connected. Lines on a plan view have no connection to the same lines presented on a section view; therefore, the possibility of uncoordinated data is very high (Demchak et al. 2009). In other words, CAD drafting is simply a digital simulation of the act of drafting. CAD drawings can be the products of various software packages with different file formats. This diversity raises the issue of interoperability, prevents project team members from sharing information rapidly and accurately, and causes numerous problems including added cost, etc. (Eastman et al. 2011). The results of a study performed by The National Institute of Standards and Technology (NIST) indicated that the lack of software interoperability cost the industry $15.8 billion annually (Gallaher et al. 2004). Even single format files or hardcopies can easily reach hundreds of drawings. Retrieving information is mostly conducted manually by jumping between files of drawings and documents. The need for dynamic interrelationships between drawings will play a major role in reducing errors and increasing productivity (Eastman et al. 2011).

Studies have revealed that the perceptive abilities of humans are remarkably faster than their cognitive system. Thus, 2D drawings are more easily recognized and comprehended if they are presented in a 3D virtual model, where geometry, form, locations, and layout of design are displayed in close-to-real life images. To improve design efficiency, the industry stepped toward 3D CAD modeling in the early 1980s. This shift better served visualization and spatial analysis, yet the model remains as a regular CAD system based on combining multi-lines to form an object (Bozdoc 2003). Conceptually, 3D CAD models enhance productivity by enabling extraction of 2D drawings from different views. However, creating a complete 3D model is time consuming and requires full-time modelers (Goldberg 2004). While the 3D entities can carry embedded data used for defining material quantities, the entities are still drawn as multi-lines and cannot be intelligently connected or parametrically defined (Goldberg 2004). Furthermore, 3D entities do not include or integrate other information regarding specifications, scheduling, bills of quantities, and performance requirement.

2.5.3 Documenting Design Rationale

The widespread adoption of various computer-aided design (CAD) systems in the current architectural/engineering/construction (A/E/C) industry has greatly aided documenting of increasingly complex projects, exchanging project information, and reducing time, cost, and errors. While these systems are excellent for documenting and representing final design task solutions through drawings and specifications, they are not capable of incorporating and recording the process by which the design was evolved (Hegazy et al. 2001; Sung et al. 2011). In other words, CAD systems do not represent the relationships among drawn objects and parameters that govern the rationale behind their attributes. This drawback can be overcome by facilitating design rationale recording and extraction of each discipline component throughout the building's design phases. Finally, this information can be utilized for checking the compliance and evaluating the minor submittal deviations during construction.

Many researches in the literature has examined the storing and capturing design rationale as being integral to managing design changes and design information. One interesting effort to capture design rationale was proposed by de la Garza and Oralkan (1992). The proposed skull object space (SOS) is a system that uses hierarchical representation to store design rationale for estimating construction costs of a building. A system developed by Ganeshan et al. (1994) has the ability to record the sequence of the decision-making process and determine the decisions affected by a change (i.e. recording the intents of relationships between building components). Shipman and McCall (1997) proposed two systems, PHIDIAS and the Hyper-Object Substrate, that attempted to capture design rationale by logging CAD designs, and allowing the searching and retrieving of captured data. The two systems, however, could not represent the captured information in a formalized or understandable manner (Sung et al. 2011). De la Garza and Alcantara (1997) presented a unique data structure which used a parameter dependency network system to capture design rationale. The system is based on representations of hierarchical building data and design rationale as performance criteria, e.g., the rationale for a certain door design is represented by a desired fire rating.

Hegazy et al. (2001) developed a notable model for storing information, for recording the design rationale for each building component to enable the coordination of the design, and for managing changes to the design (Figure 2-4). Design rationale, as proposed in the information model and described in Figure 2-4, is represented by four information items: (1) description of the desired performance criteria; (2) minimum and maximum performance values; (3) list of components affecting the current components; and (4) list of components affected by changes in the current component. The proposed model incorporates a central building components library (BCL) that is used to create a complete building project hierarchy (BPH). Although the model alerts all affected parties to any changes made to any building component, the role of the model's design administrator is addressed as the essential central coordinator.

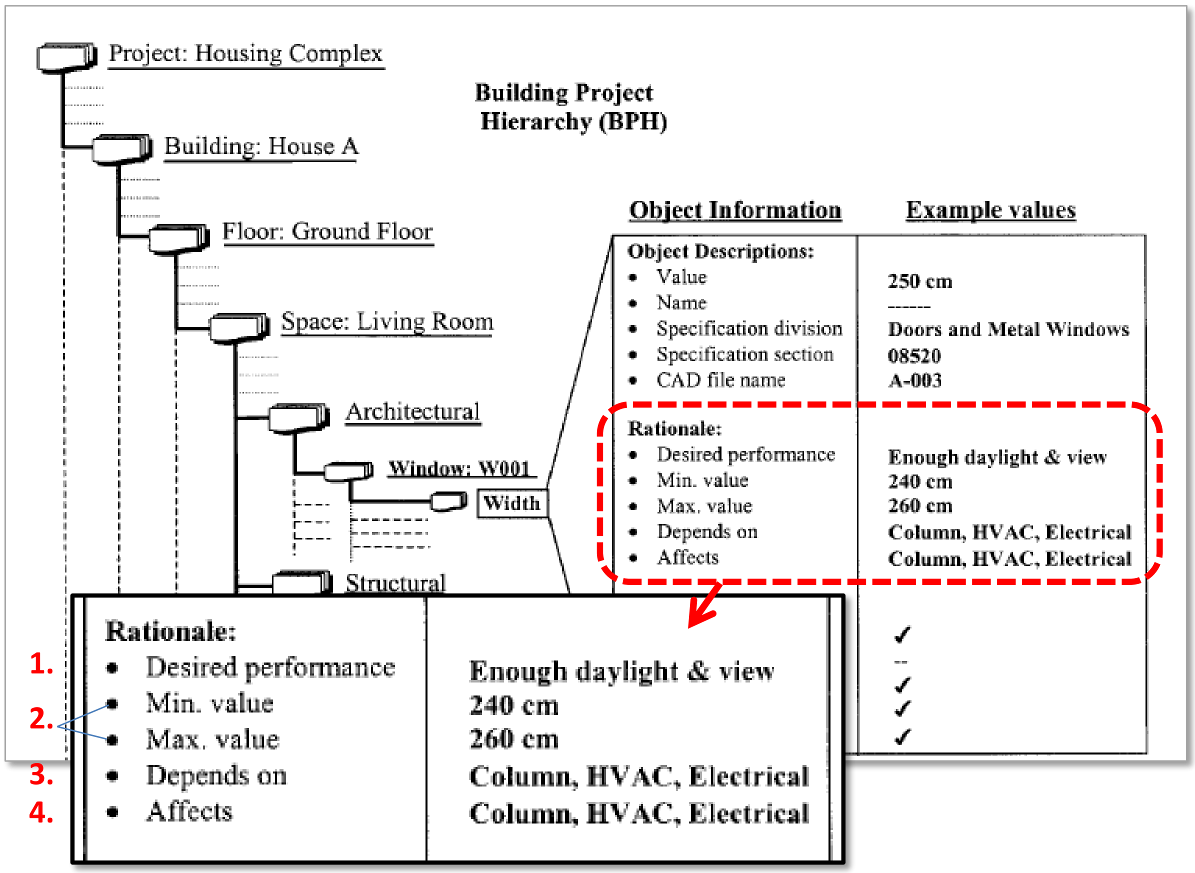


Figure 2-4: Recording Design Rationale in Four Information Items (Hegazy et al. 2001)

Recently, capturing and extracting design knowledge from CAD systems has received the attention of researchers. Jin and Ishino (2006) presented a tool that automatically extracts design activity knowledge embedded in a 2D CAD design session. Iyer et al. (2006) offered a system for automatically extracting the design intent of geometrical and textual entities from legacy CAD such as 2D drawings and 3D models. Sung et al. (2011) claimed that capturing and accessing design rationale (or design knowledge) would provide insight into the reasons behind key decisions, which in turn would support practitioners needing to make future revisions. This system could unobtrusively capture the design process and knowledge by logging individual designer behaviour during usage of a CAD system.

At this time, the ability to document design rationale in building information model (BIM) is a new field of research requiring contribution. It holds the potential to enhance design change management during design and construction phases (submittal review process) and give useful evaluative insight.

2.6 Building Information Modeling (BIM)

The logical evolution of 3D CAD is an information-rich digital model with a central repository database for all building components (Demchak et al. 2009; Wilbur 2009). In recent years, a new approach for AEC has been launched and emerged into a very active research area: Building Information Modeling (BIM). BIM promises to tackle and facilitate the problems related to information integration and interoperability throughout the lifecycle of a building, from feasibility and conceptual design to demolition and re-cycling stages (Isikdag and Underwood 2010; Hardin 2009).

2.6.1 Brief Background

Neither the conception nor terminology of BIM is new. The concept, approach and methodology identified now as BIM can be traced back approximately thirty years. In fact, the terminology of the "Building Information Model" has been in circulation for at least fifteen years. The earliest example of the concept of BIM was provided by Chuck Eastman in 1975 as a working prototype "Building Description System" (Eastman 1975). In the early 1980s, this method or approach was most commonly described in the USA as "Building Product Models" and in Europe as "Product Information Models".

The first documented use of the term "Building Modeling" appeared in the title of a 1986 paper by Robert Aish. This paper presented important arguments including 3D modeling, automatic drawing extraction, intelligent parametric components, rational database, and temporal phasing of construction processes (Aish 1986). As a BIM pioneer, Eastman discussed some limitations of the systems and concepts of Building Modeling, and identified additional concepts that could enhance the eventual production quality of Building Model (Eastman 1992). In December 1992, the term "Building Information Model" was documented on a paper presented by van Nederveen and Tolman and published in the Automation of Construction Journal (van Nederveen and Tolman 1992).

The first attempt to popularize the term "Building Information Mdeling" was introduced by Jerry Laiserin in 2002 (Laiserin 2002). Also in this year, Autodesk acquired Revit® Technology from a startup company and introduced the best-known and current market leader of BIM, entitled Revit (Demchak et al. 2009 and Eastman et al. 2011). Although the term and technology of Building Information Modeling was first commercially introduced and applied in the industry by Autodesk Revit, the concept or approach had been established more than fifteen years prior. Table 2-4 summarizes the major historical chapters of BIM since 1975.

Table 2-4: The Development of BIM Terminology

Years	Development of the Terminology	References
1975	Concept of BIM was provided as a working protoptype "Building Description System"	(Eastman 1975)
1986	First documented use of the term "Building Modeling"	(Aish 1986)
1992	Additional concepts of "Building Modeling" were identified	(Eastman 1992)
1992	The term "Building Information Model" was documented	(van Nederveen and Tolman 1992)
2002	First attempt to popularize the term "Building Information Modeling"	(Laiserin 2002)
2002	Autodesk introduced the well-known BIM software: Revit	(Eastman et al. 2011)

2.6.2 General Overview of BIM

Building Information Modeling is an emerging technology and process promising to change the tradition way of designing, analyzing, constructing, and managing buildings. BIM is not just software, but a process and software. In essence, BIM essentially not only uses a 3D modeling software to visualize and communicate, but also implements a new way of thinking (Hardin 2009). BIM exists in the spirit of not doing the same old thing. With the emergence of a new technology, it is expected that the practices and functions of professionals should definitely be changing (Hardin 2009). Although technology is the key, it is vital to define BIM and its processes.

One of the early definitions of BIM was addressed by Eastman (1999), and stated that “BIM is a digital representation of the building process to facilitate exchange and interoperability of information in digital format” (Eastman 1999). In this definition, both information exchange and interoperability were realized and expected to be a major factor affecting future building projects. According to a 2004 analysis by Stanford University’s Center for Integrating Facilities Engineering (CIFE), the productivity in the construction industry has decreased significantly over the last forty years (from 1964 through 2003) compared to all non-farm industries during the same period of time (Young et al. 2009). The graph compiled by the CIFE indicates that construction productivity declined by nearly 20% between 1964 and 2003, while other non-farm industries improved by more than 200% (Figure 2-5). This significant reduction occurred mainly because of a lack of proper communication and collaboration through information.

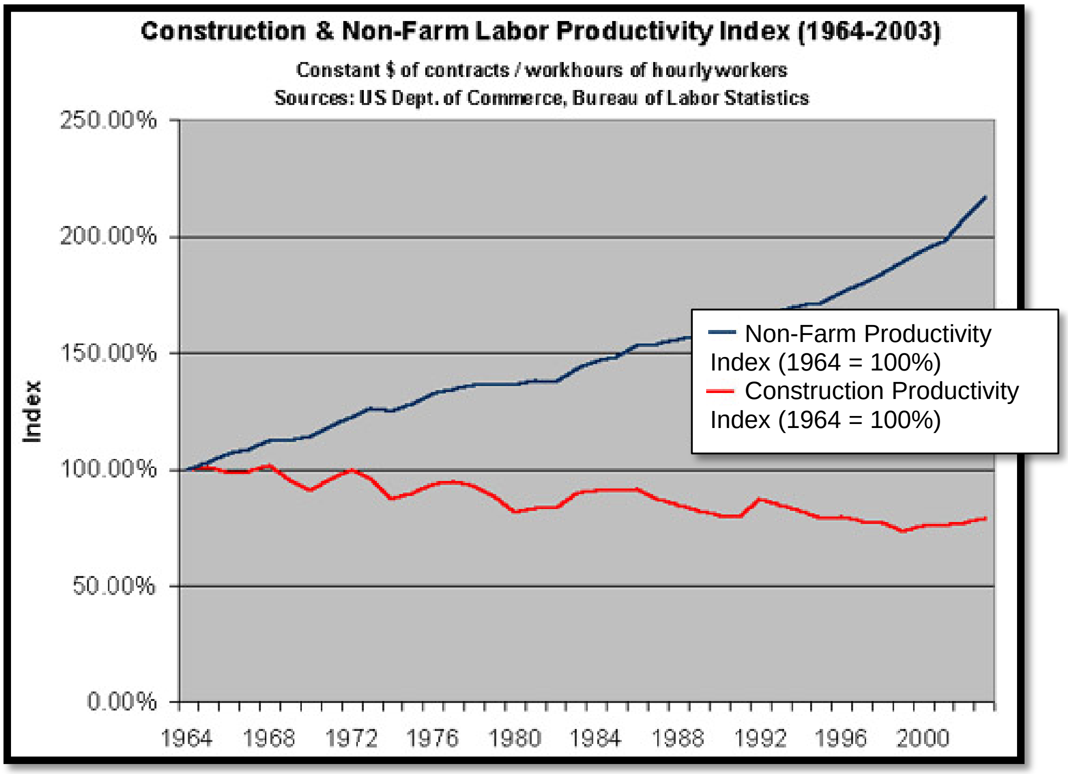


Figure 2-5: Construction Productivity Index Compared to Non-Farm Industries (Young 2009)

The American Institute of Architects has defined BIM as "a model-based technology linked with database of project information" (Lee at al. 2006). This definition reflects the general reliance on database technology as a backbone for BIM. BIM provides AEC professionals with both a geometrically accurate 3D representation of a building and the capability to integrate attributes and data to the components inside the model (Sabol 2007).

Being parametric-based (as opposed to geometric-based in traditional CAD) makes BIM remarkable. Static building objects are replaced with highly interactive and self-analytical ones (Seletsky 2004). BIM is defined by The National Building Information Modeling Standard (NBIMS) as "a digital representation of physical and functional characteristics of a facility and it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward" (Smith and Edgar 2008). It is defined also as a parametric 3D object-oriented model linking to a project database and describing dynamically functional and physical features (Birx 2005). The concept of BIM, as defined, has developed from the point of providing a parametric-based model that reflects insertion, extraction, and updating physical/functional characteristics of a building throughout the lifecycle of the building from inception to operation (NBIMS 2007).

BIM, in essence, uses 3-D parametric objects to create all architectural elements including walls, floors, roofs, windows, and doors etc., and all other building systems such as structural, mechanical, and plumbing as needed. BIM uses real-life objects to generate the 3D-model. Figure 2-6 shows a BIM platform and its real-life parametric objects.

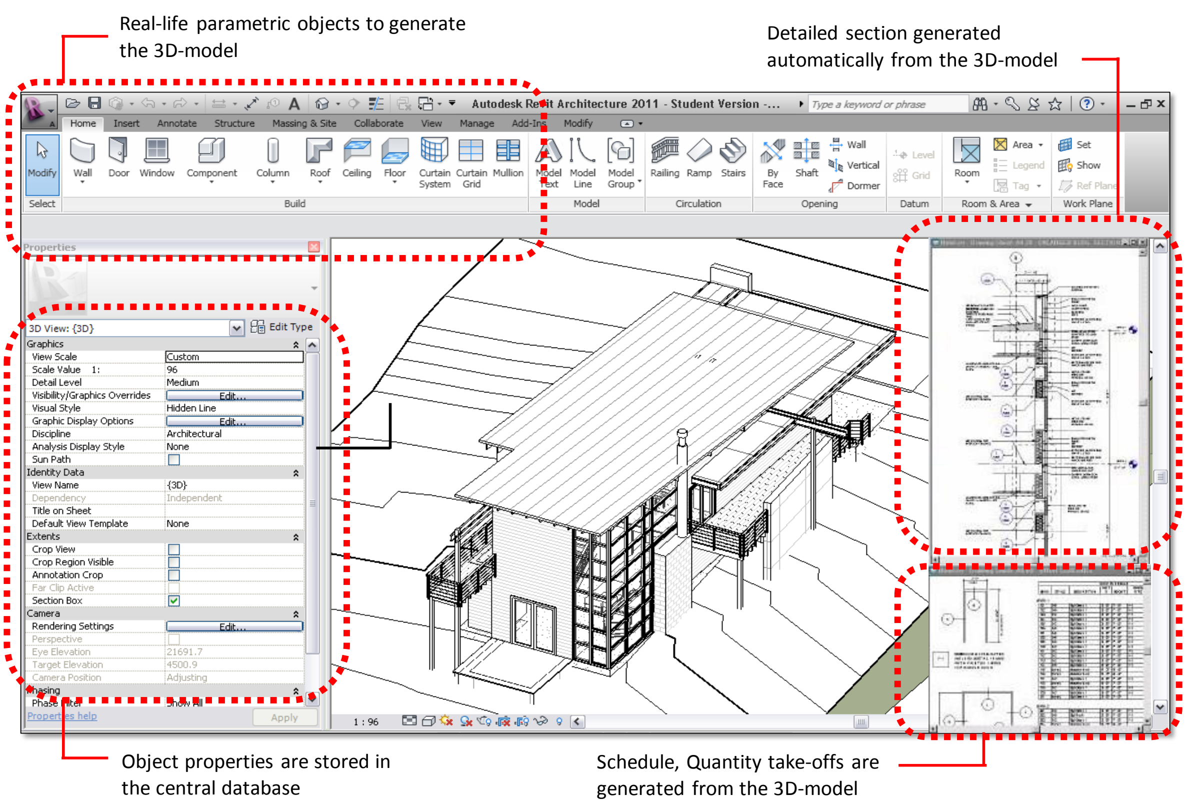


Figure 2-6: BIM Platform

The parametric objects are linked to a central database containing all information related to the geometry details, spatial relationships, and properties of the building components. Other information can be attached to the objects including manufacturers, fire rating, schedule, quantity take-offs, detailed section, and cost estimates (Birx 2005; Sabol 2007; Goedert and Meadati 2008), as illustrated in Figure 2-6. Changes in one door, for example, will affect all doors within the same category on all floors and will be reflected directly in all drawings (plans, elevations, and sections). As such, the final design becomes an intelligent information-rich model that is accurate and consistent. This design can be conveniently used to visualize the entire building lifecycle including the processes of construction, and facility operation and maintenance (Autodesk 2011).

BIM also enables the 3-D building model to incorporate and retrieve all Construction Documents, including procurement details, environmental conditions, submittal processes, and other specifications for building quality (Azhar et al. 2008; Goedert and Meadati 2008). It is anticipated that BIM can be utilized to bridge the information loss associated with handing a project from design team to construction team and to building owner/operator, by allowing each group to add and refer back to all information acquired during their period of contribution to the BIM model (Holness 2006; Autodesk 2011). BIM provides the potential for a virtual information model to be handed from design team (architects, surveyors, civil engineers, structural engineers, mechanical engineers, electrical engineers) to contractor and subcontractors and then to owner, with each adding their own additional discipline-specific knowledge and tracking of changes to the single model.

BIM is an emerging technology to the construction industry and its adoption by all project parties appears to be significantly increasing. The General Services Administration (GSA) has recognized the benefits of BIM. By the beginning of fiscal year 2006, all AEC firms dealing with the GSA had to include the BIM as part of the work proposal (Silver 2005). The 2009 SmartMarket Report published by McGraw-Hill construction stated that about 50% of the U.S. building industry was using BIM, a 75% increase since 2007 (Young et al. 2009). The report revealed that six out of ten architects in the United States created BIM models, with 50% of these users also performing analysis In addition, the report stated that over the next two years the use of BIM was expected to double by structural engineers, triple by mechanical, electrical, and plumbing (MEP) engineers, and quadruple by civil engineers. According to the report, the use of BIM among U.S. contractors had almost quadrupled in the past two years, with 50% of all contractors currently using BIM.

In addition to the above unique functions of BIM, it has been claimed that a building information model can be exploited for creative purposes including fabrication, code reviews, forensic analysis, facilities management, cost estimation, and conflict or collision detection (Brix 2005; Azhar et al. 2008).

2.6.3 BIM Platforms

In this section, a summary is provided of the major functional and performance capabilities that distinguish different BIM platforms. All BIM platforms are supported with tools to create, edit, and manage objects and provide a standard set of predefined parametric objects that can be expanded and customized. While all BIM platforms are directed to the AEC industry, some are specialized in specific disciplines, such as Bentley Systems, a major player in civil engineering and infrastructure marketplace. Table 2-5 presents a summary of major BIM platforms available in literature. The major BIM platforms provide a complete solution for all phases of building design and construction. However, BIM platforms are not a decision support tool, thus, critical decisions cannot be efficiently taken based on BIM platforms alone.

Table 2-5: Major BIM Platforms

BIM Systems	Features
Autodesk Revit (Khemlani 2011a)	The best-known and current market leader of BIM technology. It is a strong, easy-to-use, and affordable BIM platform. Integrated design practice is well-established. Construction methods can be added to building components. Collaboration is facilitated through the Revit Server and Vault. Customizable by Revit Application Programming Interface (API).
Bentley Systems (Eastman et al. 2011)	A major player in civil engineering and infrastructure marketplace. User-defined Macros are supported. More time to learn and navigate.
ArchiCAD (Eastman et al. 2011; Khemlani 2011b)	Well-crafted interface with smart cursor. Easy-to-use freeform modeling tool. Object classes can be customized by Geometric Description Language (GDL). Availability of useful add-ons including Virtual Building Explorer, MEP Modeler, and EcoDesigner. Can not be used for fabrication details.
Vectorworks (Eastman et al. 2011; Khemlani 2011c)	A cost-effective BIM alternative. Relies on exporting to spreadsheets for quantity takeoffs. Supported with strong Industry Foundation Class (IFC) exchange capabilities. Supported with a powerful API and scripting capabilities.
Tekla Structures (Eastman et al. 2011; Khemlani 2010)	A structural engineering software that is most widely used for detailing steel and concrete construction. Complex application that still relies heavily on numeric input in dialogs for many operations.
Digital Project (Eastman et al. 2011)	A platform used to develop complex and curved parametric assemblies. It has links to MS Project and Primavera Project Planner for scheduling, and to ENOVIA for project lifecycle management. Supported with strong API and Visual BASIC scripting. Facilitates the integration of specifications (Masterformat) and cost estimating (Uniformat).
Dprofiler (Eastman et al. 2011)	A unique product in addressing conceptual design from a cost of construction point of view. Used for financial evaluation of a construction project.

2.6.4 BIM Collaboration Software

BIM tools or platforms are not meant to be a complete solution for construction management tasks. External tools are developed to play the role of linking or synchronizing the BIM model with scheduling, planning, cost estimating, and clash detection. The major tools are provided by Autodesk Navisworks and Solibiri.

1. Autodesk Navisworks

Autodesk Navisworks was originally available as a single application with multiple components known as Jetstream. It was acquired by Autodesk in 2007 and has since been enhanced to be three separate paid stand-alone applications that are targeted for a variety of users (Khemlani 2008). The Autodesk 2011 version of Navisworks included three separate products; Autodesk Navisworks Freedom, Autodesk Navisworks Simulate, and Autodesk Navisworks Manage.

The Freedom viewer is useful for those who might want to look at the composite model overall but who do not want to purchase the full version or any licenses of Navisworks. Navisworks Manage belongs at the top level of the Navisworks product line-up and allows users to make use of the full capabilities and features of Autodesk Navisworks products. The three applications share the major capabilities of 3D real-time visualization, navigation, and review. The model aggregation, collaboration, and 4D scheduling and analysis features are available in the Navisworks Simulate and Navisworks Manage products. The tools that allow users to perform clash and interference detection are only available in Navisworks Manage product (Autodesk 2010). Table 2-6 summarizes the comparison between the three products of Navisworks in terms of products features.

Table 2-6: Comparison of Navisworks Products (Autodesk 2010)

Feature	Autodesk Navisworks *Manage*	Autodesk Navisworks *Simulate*	Autodesk Navisworks *Freedom*
Project Viewing			
Real-Time 3D Visualization & Navigation	●	●	●
Whole Team Review	●	●	●
Project Review			
File & Data Aggregation	●	●	
Review Toolkit	●	●	
Collaboration Tooolkit	●	●	
Simulation & Analysis			
Photorealistic Visualization	●	●	
Object Animation	●	●	
4D Sheduling	●	●	
Coordination			
Clash & Interference Detection	●		
Clash & Interference Management	●		

Autodesk Navisworks is a powerful tool enabling design and building professionals to unite project contributions into a synchronized model for BIM (Hardin 2009). Navisworks conveniently and innovatively utilizes the full benefits of BIM models and processes. Navisworks is not a modeling program; rather, it links BIM and 3D files (regardless of file size) into a Navisworks format (NWD), that can be viewed, explored, and analyzed using any viewer of the Navisworks family: Manage, Simulate, or Freedom (Hardin 2009; Khemlani 2008; Autodesk 2010).

As such, Navisworks provides the project stakeholders with the right tools to make better design decisions, improve accuracy of construction documentation, enhance levels of interoperability, and increase productivity (Autodesk 2010).

2. Solibri Model Checker

Solibri provides a world class model checking solution which not only helps design superior buildings but also accelerates the transition to model based collaboration. Solibri Model Checker is surprisingly well assembled, and is relatively easy to use. The 3D visualization interface is excellent, and the three different components of the application are optimally organized. Visualizing the checking of results is particularly well implemented; for example, the sectioning capability works in conjunction with the spatial coordination results, thus allowing viewing of issues while the model is sectioned (Khemlani 2009). Solibri Model Checker is quite suitable for use by design firms as their internal QA tool to improve model quality and consistency. It can also be used by contractors to validate that models received from the design team meet their specific criteria as captured in their own customized rule sets (Khemlani 2009).

2.7 Multi-Criteria Decision Analysis (MCDA)

Submittal evaluation involves analysis of several alternatives and consideration of multiple criteria and the process therefore falls into the category of Multi-Criteria Decision Analysis (MCDA) (Zeleny 1981). MCDA tools and techniques can consider criteria that are either quantitative and measurable, such as material thickness, or subjective and difficult to measure, such as colour and aesthetics. Submittals often include both types of criteria. Door specifications, for example, might list a thickness of 500 mm as a quantitative criterion, and “dark grey colour” as a qualitative criterion.

MCDA techniques are distinguishable from one another principally in terms of how basic information is processed. Some MCDA techniques that are most relevant to submittals evaluation are linear additive models, the analytical hierarchy process (Ababutain 2002), and the multiple attribute utility theory. Discussion of alternative approaches to solving problems associated with MCDA are found in various studies, such as Belton and Stewart (2001), Hipel (1992), Hipel et al. (1993; 1999), Hobbs and Meier (2000), Roy (1996) and Saaty (1980; 2001). The three techniques that are related to submittal evaluation are discussed briefly in the following subsection.

2.7.1 Linear Additive Model

A linear additive model is used when the criteria are independent of one another and when uncertainty is not formally built into the MCDA model. The linear model shows how an alternative's values based on many criteria can be combined into one overall value. The value score for each criterion is multiplied by the weight of that criterion, and then the weighted scores are added together. However, this simple arithmetic is appropriate only if the criteria are mutually independent. In linear additive models, MCDA is commonly applied in two stages:

1. Scoring: The expected consequences of each alternative are assigned numerical values.

2. Weighting: For each criterion, a numerical weight is assigned that defines its relative contribution to the final decision. The overall preference score, or value, for each alternative is simply the weighted summation of its values for all the criteria. Letting the preference value for alternative i on criterion j be represented by V_{ij} and the weight for each criterion be W_i, then for q criteria. The overall score, v^i, for the i^{th} alternative, can be calculated as follows:

$$V_i = V_{i1}W_1 + V_{i2}W_2 + V_{i3}W_3 + \ldots \ldots + V_{ia}W_q = \sum_{j=1}^{a} . V_{iq}W_q$$

Thus, scoring and weighting are the most challenging aspects of MCDA techniques. The above method is suitable if all data can be expressed quantitatively. For some decision problems, criteria or alternatives are difficult to express entirely in a quantitative form, or are not feasible in certain situations. It is then recommended that the elimination method be used, which has the advantage of allowing the alternatives to be ranked without using quantitative weights.

2.7.2 The Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), initially developed by Thomas L. Saaty (1980; 1990) in the 1970s, is an effective and popular method for solving multi-criteria decision-making problems (Zahedi 1986; Shim 1989; Pan 2008). AHP involves the principles of decomposition, pair wise comparisons, and priority vector generation and synthesis (Duran 2011). AHP uses procedures for deriving the weights and the scores achieved by alternatives, which are based, respectively, on the pair wise comparisons of criteria and of alternatives. Thus, for example, in assessing weights, the Decision Maker (DM) is posed a series of questions, each of which asks how important one particular criterion is relative to another for the specific decision being addressed.

AHP has several advantages, including its acceptance of inconsistencies in managerial judgments/perceptions, ease of use and understanding, flexibility, and wide applicability, (Ho 2008; Alias et al. 2009; Duran 2011). In addition, the use of AHP does not involve cumbersome mathematics and it can effectively handle both qualitative and quantitative data (Duran 2011).

The strengths and weaknesses of the AHP have been the subject of substantial debate among specialists in MCDA (Zahedi, 1986; Shim, 1989; Goodwin and Wright, 1998; and French 1988). More recently, Saaty (2001) has developed the Analytic Network Process (ANP), which is a generalization of AHP.

2.7.3 Multi-Attribute Utility Theory (MAUT)

The breakthrough in multi-attribute utility theory (MAUT) was the work of Keeney and Raiffa (1976). They developed MAUT, in which a set of procedures allows decision makers to evaluate alternatives against multiple criteria. Their procedure establishes a utility function for each criterion, as a representation of a pre agreed-upon satisfaction level associated with different values for that criterion. A sample utility function is provided in Figure 2-7, which shows the utility values of 1.0, 0.7, 0.5, 0.3 and 0.0 associated with contractors' years of experience (criterion) of 15, 12, 9, 6 and 3 years, respectively. In this case, the utility value (0 to 1.0) on the vertical axis represents the pre-agreed-upon level of satisfaction for the criterion values. The benefit of determining a pre-set utility function, therefore, is to remove bias decision process and to facilitate the automatic evaluation of possible decisions.

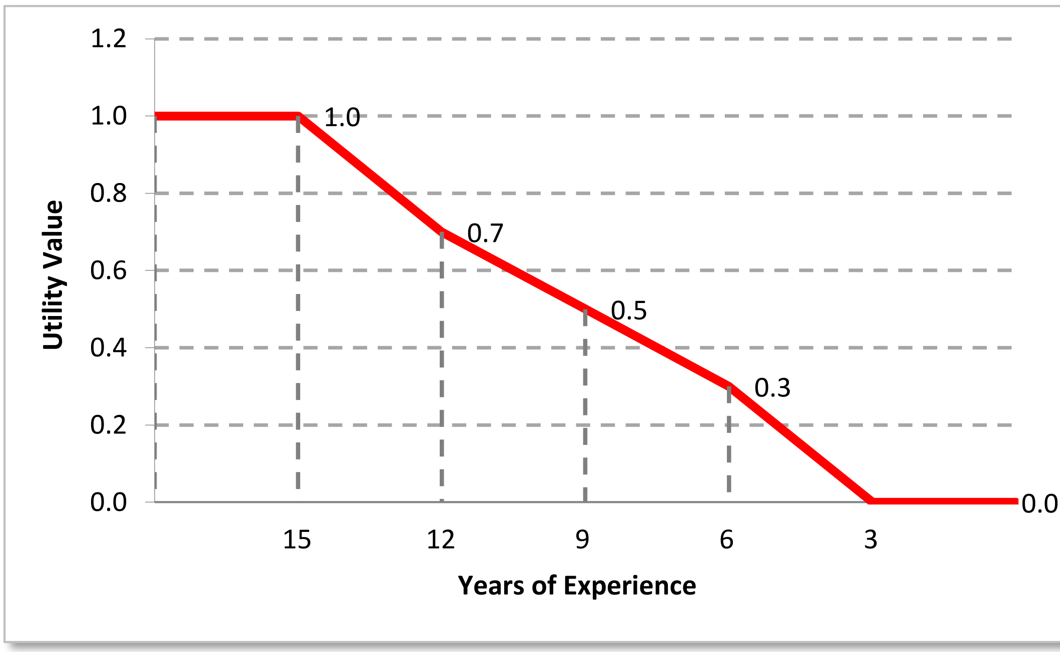


Figure 2-7: Utility Functions for the "U-Value" Criterion of a Window

In the case of decisions involving multiple criteria, the alternative that maximizes the total expected utility, considering the criteria weights, is selected (Kilgour 2007). In other words, when utility analysis is used and the criteria are known to the contractors before they submit the material, they will try to maximize the item's utility in order to speed up the approval process and avoid any cost implications.

A critical step in MAUT analysis is the determination of a suitable utility function form for each criterion. With this goal, several studies have been carried out, such as those by Halter and Dean (1971), Keeney and Raiffa (1976), Musser et al. (1984), Pena-Mora and Wang (1998), Zuhair et al. (1992), Kersten (2001), and Zeleznikow et al. (2007). In this research, the form of a utility function is generated for the critical architectural submittals based on the preferences and feedback values of the consultant and his/her organizational objectives.

However, among MAUT's benefits is the fact that utility functions can be determined differently to reflect the risk attitude (or tolerance) of the decision maker with respect to various criterion values. Figure 2-8 shows three utility functions representing three types of risk attitudes: risk-averse, risk-seeking, and risk-indifferent. When each criterion has been presented with one of these utility functions and the relative weights of the criteria are known, the analysis process becomes dynamic, responsive to the preferences of decision makers (DMs), and simple to automate. Such benefits make MAUT analysis suitable for developing a decision support system (DSS) for submittals evaluation.

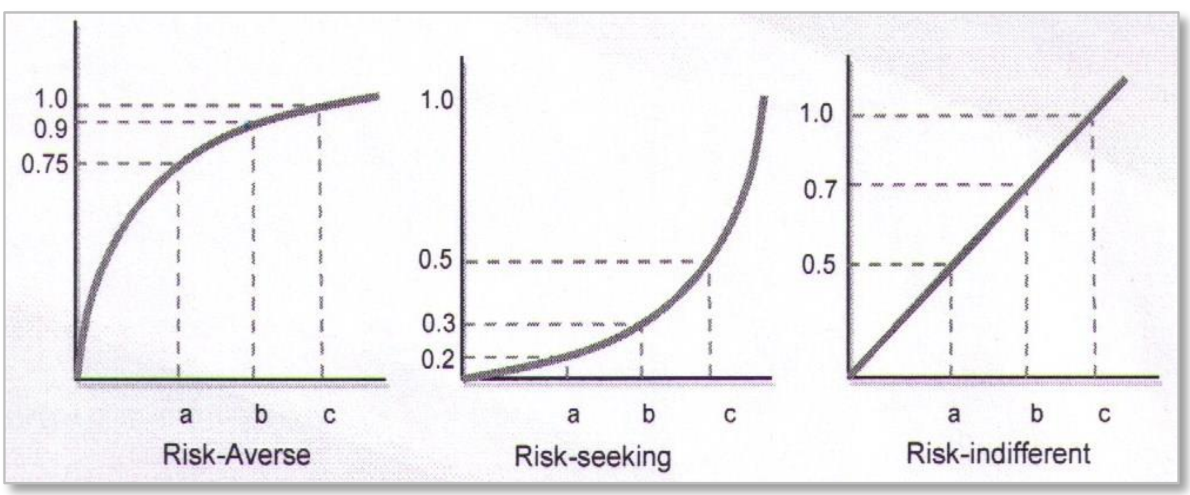


Figure 2-8: Different Utility Functions with Different Risk Attitudes (Moore 2001)

2.8 Conclusion

This research has been initiated with an extensive literature review to define submittals problems and to investigate available tools and systems. Architectural components in building enclosure have been presented to give a general idea about the behavior of the enclosure. The problems associated with design documentation have been addressed along with specification, drawings, and design rationale. Building Information Modeling (BIM) has been introduced as a promising technology and process to overcome the problem of communication, to manage all building components in a visualized way, and to keep all project parties equally informed. As the submittal evaluation process involves analysis of several alternatives, Multi-Attribute Utility theory (MAUT) and Analytical Hierarchy Process (AHP), as Multi Criteria Decision Analysis techniques, have been investigated and discussed.

Chapter 3

Analysis of Architectural Submittals

3.1 Introduction

The goal of the work presented in this chapter was the identification of the specific elements of architectural submittals that are the most critical and that require special treatment during the submittal evaluation process. The sources and types of data collected are reviewed, and the analysis conducted in conjunction with the identification process is explained. During the data collection process, the criteria for evaluating the most critical items were identified for further application and utilization in the development of the framework. The effects of aesthetics-related criteria that were suggested based on the data collection process are also discussed.

3.2 Objectives of Data Collection

The data for this study were collected with the goal of defining the architectural items that are the most critical and require special consideration during the submittal evaluation process. Because the required data needed to be collected from a variety of sources, governmental organizations as well as architectural and engineering (A/E) firms were contacted as possible providers of documents and feedback. Two organizations and two A/E firms agreed to contribute to this study. An item was determined to be critical based on analysis of the submittal logs and practitioners' feedback provided by these organizations and firms. Collecting the essential data involved the distribution of a survey sheet and extensive interviews with the practitioners. The general approach employed is illustrated in Figure 3-1.

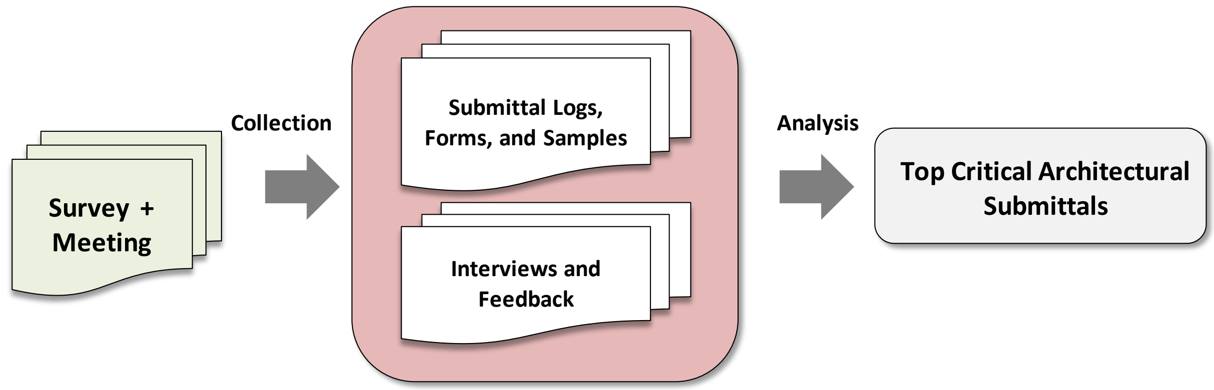


Figure 3-1: General Approach

3.3 Sources of Data

For the purposes of this study, acquiring data from different A/E sectors was necessary in order to ensure consistency and reliability. The governmental organizations were selected because of their outstanding roles with respect to the management and operation of a significant number of public projects, and the private A/E firms were chosen based on their experience with different types of projects: commercial, residential, and institutional.

Two governmental organizations were approached for this study: the Toronto District School Board (TDSB) and the Umm Al-Qura University (UQU) Department of Project Management in Saudi Arabia (www.uqu.edu.sa). The TDSB is considered the largest school board in Canada, and it owns, operates, and renovates a substantial number of building assets, ranging from schools to administrative buildings. The UQU Department of Project Management handles construction projects valued at about $258 million for the new UQU campus, including multi-level institutional buildings, an academic hospital, and housing for faculty members. The private A/E firms are Parsons Inc. of Saudi Arabia and Robertson Simmons Architects Inc. (RSA) in Waterloo, Canada. These firms have significant experience in the design and construction management of several public and private projects. All of the experienced practitioners who agreed to share their knowledge and feedback have full authority to review and approve architectural submittals combined with at least 10 years of experience in the construction industry. The surveys were completed during face-to-face interviews, and all other documents requested were collected for further analysis. Table 3-1 lists the organizations and A/E firms, the initials of the participating practitioners, and their related disciplines. Their names have been withheld for privacy reasons.

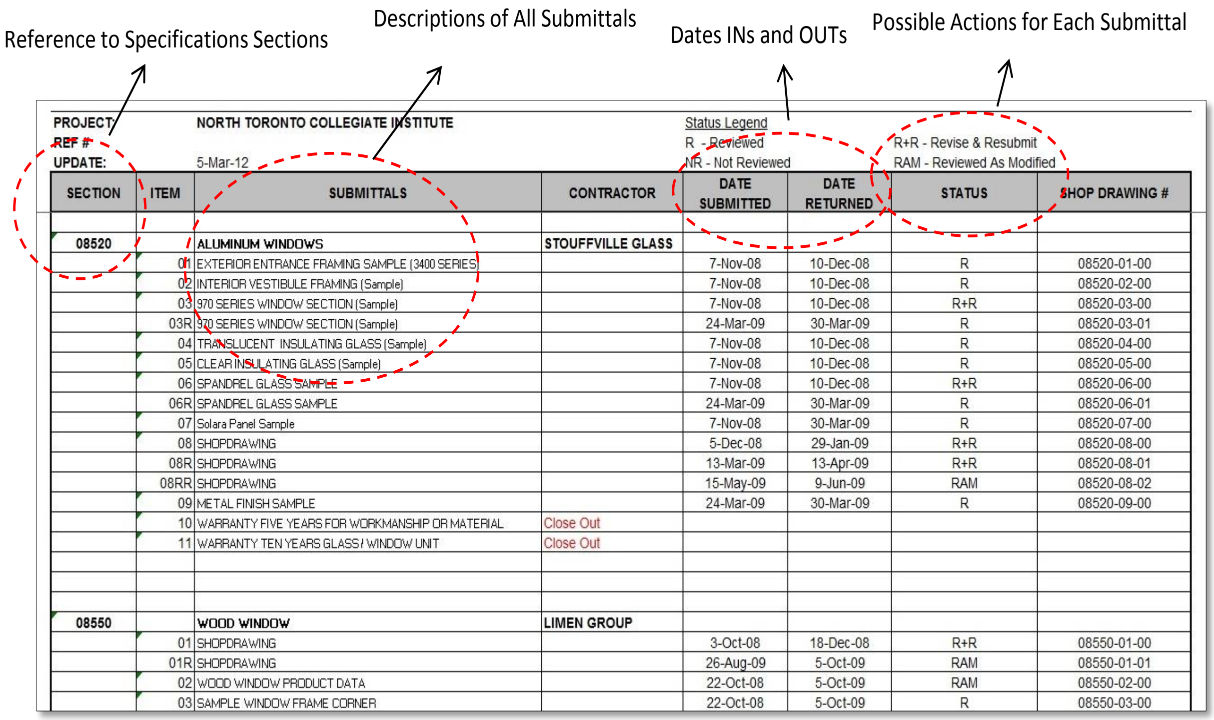
Table 3-1: Sources of Data and Participating Practitioners

Paticipating Practitioners		Practitioner's Initial	Discipline	Department
Governmental Organizations	TDSB	Eng. E	Civil Engineer	Project Supervision
	UQU	Eng. A	Architect	Project Management
Private Firms	Parsons	Eng. S	Mechanical Engineer	Project Management
	RSA	Arch. L	Architect	Architectural Design

3.4 Data Collected

Three types of data were collected from TDSB and UQU for this research: submittal logs; architectural submittal packages for previous projects, including shop drawings and submittal transmittal forms; and samples of project specifications. Along with the feedback contributed by the practitioners, these real-life data were used as a solid reference for acquiring an understanding of the factors considered in evaluating the criticality of architectural submittal items. The architectural items that are the most critical and that need special attention during the submittal evaluation process were defined based on the analysis of the submittal records. Appendix A includes samples of the data collected.

Submittal logs were collected as a means of obtaining an indication of the processing time required for each submittal registered. In general, logs are updated sheets that summarize the details of all of the submittals: specification section, description of submittal, dates IN and OUT, and review status. Four possible actions can be taken for each submittal listed in the logs: Reviewed (R); Not Reviewed (NR); Revise and Resubmit (RR); and Reviewed as Modified (RAM). A sample submittal log provided by the TDSB for a completed project is shown in Figure 3-2. Appendix A includes additional samples of submittal logs collected.



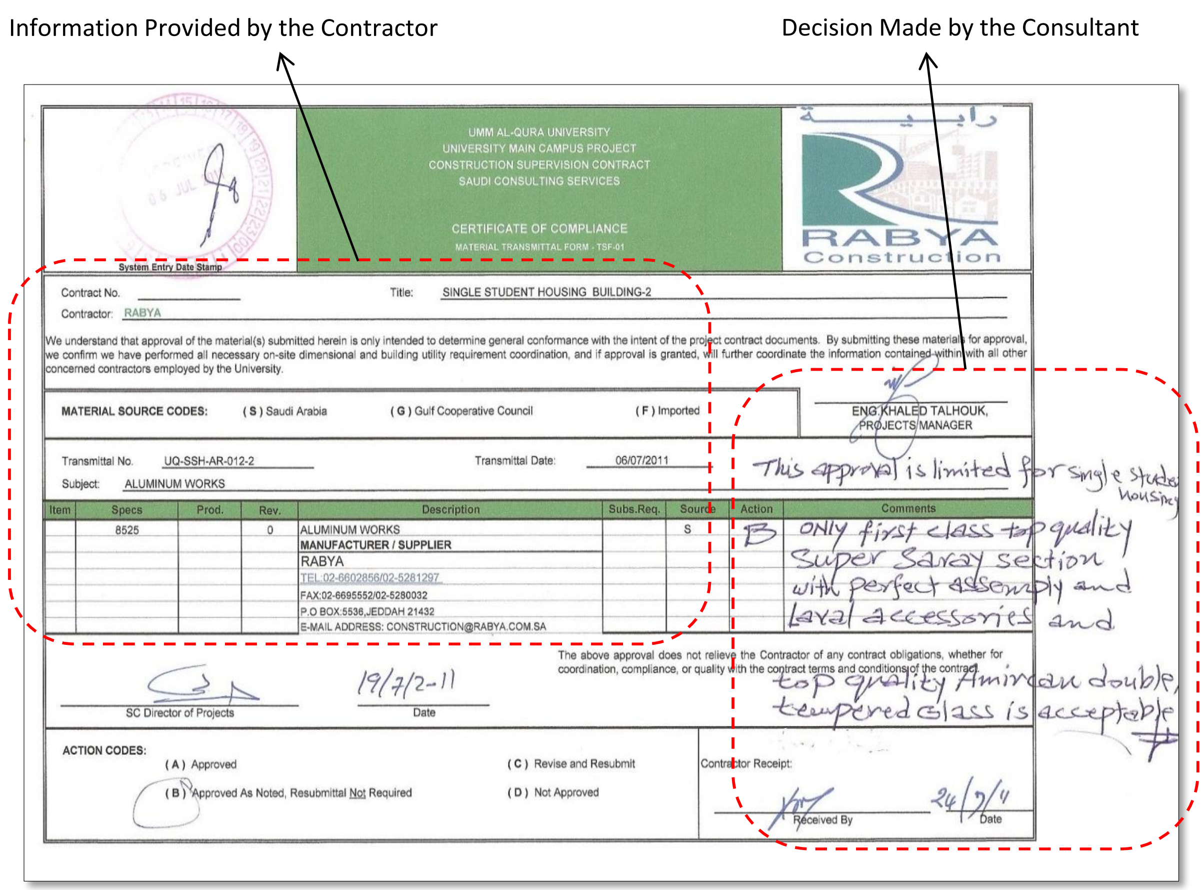
PROJECT: NORTH TORONTO COLLEGIATE INSTITUTE
REF #
UPDATE: 5-Mar-12

Status Legend
R - Reviewed
NR - Not Reviewed
R+R - Revise & Resubmit
RAM - Reviewed As Modified

SECTION	ITEM	SUBMITTALS	CONTRACTOR	DATE SUBMITTED	DATE RETURNED	STATUS	SHOP DRAWING #
08520		ALUMINUM WINDOWS	STOUFFVILLE GLASS				
	01	EXTERIOR ENTRANCE FRAMING SAMPLE (3400 SERIES)		7-Nov-08	10-Dec-08	R	08520-01-00
	02	INTERIOR VESTIBULE FRAMING (Sample)		7-Nov-08	10-Dec-08	R	08520-02-00
	03	970 SERIES WINDOW SECTION (Sample)		7-Nov-08	10-Dec-08	R+R	08520-03-00
	03R	970 SERIES WINDOW SECTION (Sample)		24-Mar-09	30-Mar-09	R	08520-03-01
	04	TRANSLUCENT INSULATING GLASS (Sample)		7-Nov-08	10-Dec-08	R	08520-04-00
	05	CLEAR INSULATING GLASS (Sample)		7-Nov-08	10-Dec-08	R	08520-05-00
	06	SPANDREL GLASS SAMPLE		7-Nov-08	10-Dec-08	R+R	08520-06-00
	06R	SPANDREL GLASS SAMPLE		24-Mar-09	30-Mar-09	R	08520-06-01
	07	Solara Panel Sample		7-Nov-08	30-Mar-09	R	08520-07-00
	08	SHOPDRAWING		5-Dec-08	29-Jan-09	R+R	08520-08-00
	08R	SHOPDRAWING		13-Mar-09	13-Apr-09	R+R	08520-08-01
	08RR	SHOPDRAWING		15-May-09	9-Jun-09	RAM	08520-08-02
	09	METAL FINISH SAMPLE		24-Mar-09	30-Mar-09	R	08520-09-00
	10	WARRANTY FIVE YEARS FOR WORKMANSHIP OR MATERIAL	Close Out				
	11	WARRANTY TEN YEARS GLASS / WINDOW UNIT	Close Out				
08550		WOOD WINDOW	LIMEN GROUP				
	01	SHOPDRAWING		3-Oct-08	18-Dec-08	R+R	08550-01-00
	01R	SHOPDRAWING		26-Aug-09	5-Oct-09	RAM	08550-01-01
	02	WOOD WINDOW PRODUCT DATA		22-Oct-08	5-Oct-09	RAM	08550-02-00
	03	SAMPLE WINDOW FRAME CORNER		22-Oct-08	5-Oct-09	R	08550-03-00

Figure 3-2: Sample Submittal Log Provided by the TDSB

Submittal transmittal forms are the second type of data collected from the TDSB and UQU. They are prepared by the contractor and cover all of the information required for identifying each submittal. In general, they are intended to provide a description of the submitted item in terms of its type (i.e., material submittal, sample, or shop drawing), the related discipline, and the supplier and/or manufacturer and also to provide a reference to the associated specifications section to facilitate a further compliance check. It is the responsibility of the A/E consultant to verify that the item complies with drawings and specifications and that is consistent with project conditions. The consultant is also responsible to makes a decision based on his/her level of experience and satisfaction with the degree of compliance. Once the evaluation is completed, the form is returned to the contractor for further consideration. A sample of aluminum works transmittal form provided by UQU is shown in Figure 3-3. The sample form indicates the main information provided by the contractor, the action taken, and the comments made by the A/E consultant (evaluator). Appendix A includes samples of architectural submittal transmittals collected from the various data sources.



UMM AL-QURA UNIVERSITY
UNIVERSITY MAIN CAMPUS PROJECT
CONSTRUCTION SUPERVISION CONTRACT
SAUDI CONSULTING SERVICES

CERTIFICATE OF COMPLIANCE
MATERIAL TRANSMITTAL FORM - TSF-01

RABYA Construction

System Entry Date Stamp

Contract No. ______ Title: SINGLE STUDENT HOUSING BUILDING-2

Contractor: RABYA

We understand that approval of the material(s) submitted herein is only intended to determine general conformance with the intent of the project contract documents. By submitting these materials for approval, we confirm we have performed all necessary on-site dimensional and building utility requirement coordination, and if approval is granted, will further coordinate the information contained within with all other concerned contractors employed by the University.

ENG.KHALED TALHOUK, PROJECTS MANAGER

MATERIAL SOURCE CODES: (S) Saudi Arabia (G) Gulf Cooperative Council (F) Imported

Transmittal No. UQ-SSH-AR-012-2 Transmittal Date: 06/07/2011

Subject: ALUMINUM WORKS

This approval is limited for single student housing

Item	Specs	Prod.	Rev.	Description	Subs.Req.	Source	Action	Comments
	8525		0	ALUMINUM WORKS **MANUFACTURER / SUPPLIER** RABYA TEL:02-6602856/02-5281297 FAX:02-6695552/02-5280032 P.O BOX:5536,JEDDAH 21432 E-MAIL ADDRESS: CONSTRUCTION@RABYA.COM.SA		S	B	ONLY first class top quality Super Saray section with perfect assembly and laval accessories and

The above approval does not relieve the Contractor of any contract obligations, whether for coordination, compliance, or quality with the contract terms and conditions of the contract.

top quality Amircan double, tempered Glass is acceptable

SC Director of Projects Date 19/7/2-11

ACTION CODES:
(A) Approved
(B) Approved As Noted, Resubmittal Not Required
(C) Revise and Resubmit
(D) Not Approved

Contractor Receipt:
Received By Date 24/7/11

Figure 3-3: Sample Submittal Transmittal Form for Aluminum Works (UQU)

As shown in Figure 3-3, the contractor provided an architectural submittal transmittal to the consultant for review and evaluation purposes. The initiation of a submittal begins with the assignment of a unique transmittal number and the documenting of the date the submittal is turned in to the A/E consultant. The contractor can typically expect a reply from the consultant within about 14 business days. The transmittal is referenced to a specific division in order to ensure compliance with the related technical specifications. In the case documented in Figure 3-3, the first line under the green bar indicates that Division 8525 of the Aluminum Works division is the reference used by the contractor for this submittal. Once the submittal is received by the consultant, a full review must be conducted before a final decision can be rendered. In this sample, the review of the submittal took 18 days, with the resulting action categorized as “B”: Approved as Noted.

Submittals forms are essential for ensuring compliance with drawings and specifications. However, the criteria that are used to check for compliance are either not fully identified or are undocumented altogether (lack of criteria). The process is thus time consuming, and because the final decision is based on the level of experience of the individual evaluator, it is also subjective. A review of some of the forms revealed that the decision not to accept some items was based solely on the consultant’s opinion and without solid justification. Others were accepted based on partially compliant information provided without reference to the original construction documents. In fact, some specifications were either incomplete or entirely lacking.

To identify the criteria that specify the technical requirements for architectural work and products, sample specifications were requested. A complete package of technical specifications was collected from UQU for the planning and design of the UQU campus; other samples of specifications were also collected from the other data sources. The level of detail in these samples varied considerably. Design standards and reliable testing measures, such as those published by the Canadian Standards

Association (CSA), should act as the baseline reference for controlling the consistency of such details; however such is not always the case. It is the task of the specifications writer to ensure that the details are compatible with both the project requirements and the performance level required. Due to a shortage of time and resources or lack of experience, some parts of the specifications examined were expressed roughly with only minimum details, which create an opportunity for modifications or even deviations, which may negatively affect the project in the long run. It should be noted that the absence of defined criteria may also lead to difficulties and cause time-consuming problems during the evaluation of the submittal.

3.5 Identifying Critical Architectural Submittals

The process of identifying critical architectural submittals involved two steps: analyzing the submittal logs collected and soliciting feedback from experienced practitioners. In the first step, complete sets of submittal logs for two projects (a total of 358 registered submittals) were analyzed in order to identify the critical building submittals. The initial analysis indicated that architectural submittals contained the largest number of submitted items, with 233 records (65 %). Mechanical submittals involved the second greatest number, representing 20 % of all submittals, followed by 8 % and 7 % for structural and electrical submittals, respectively. Part (a) of Figure 3-4 illustrates the initial analysis results for all of the submittals recorded.

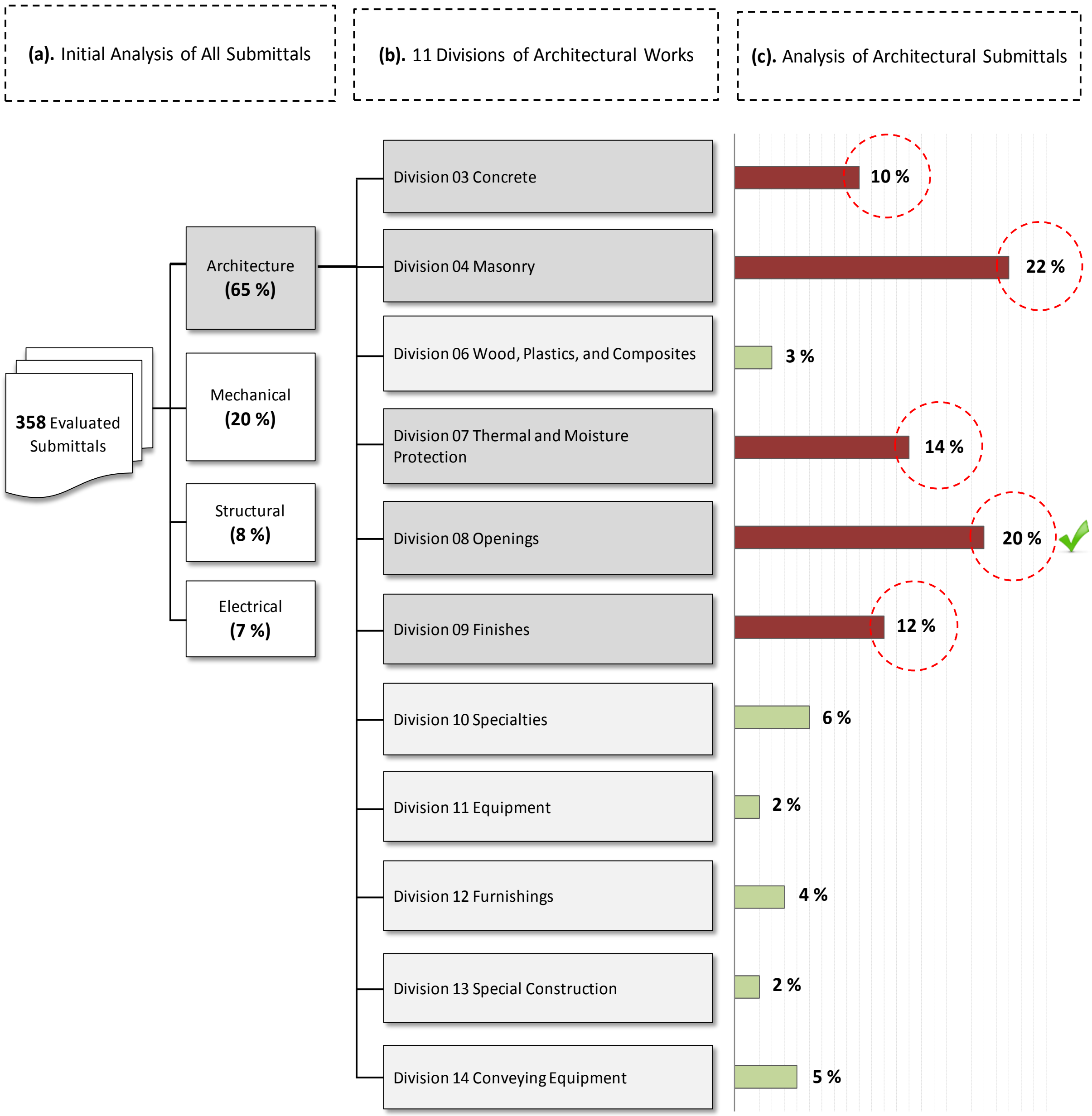


Figure 3-4: Analysis of Submittal Logs

Further analysis of the architectural work included in the collected logs identified submittals in 11 specific divisions of *MasterFormat 2004*, as shown in part b of Figure 3-4. Each division is comprised of several subdivisions that cover all of the work and products submitted for evaluation. It is assumed that a greater number of subdivisions require additional time, effort, and experience in order to produce effective decisions that support the successful overall performance of the project. Based on this assumption, an analysis of the architectural divisions and their related subdivisions was conducted, which revealed that Division 04 Masonry involved the largest number of registered submittals, with 51 records (22 %), followed by Division 08 Openings, with 47 registered submittals (20 %). With 33 subdivisions that represent about 14 % of all divisions, Division 07 Thermal and Moisture Protection fell in third place in the analysis, followed by Division 09 Finishes and Division 03 Concrete, which had only 12 % and 10 %, respectively. Part (c) of Figure 3-4 illustrates the ranking results of the frequency analysis of the architectural submittals.

The next step involved consultations with industry practitioners as a means of examining the criticality of the five most frequently occurring architectural submittals. During several rounds of interviews, it was established that a critical component could be defined as one that (1) is an essential part of the building envelop that affects the overall performance of the building (i.e., energy consumption, cost of operation, level of satisfaction, etc.); (2) involves a process of procurement, testing, and commissioning; (3) requires a specialized process for customization, fabrication, installation, and maintenance; (4) adds aesthetic value; and (5) requires extra time and a high level of experience for evaluation and approval. These criticality measures cover construction and operational aspects without compromising non-quantitative elements: aesthetic and architectural features.

According to the feedback received from the practitioners, while Division 04 Masonry was associated with the largest percentage of total architectural submittals (part c of Figure 3-4), Division 08 Openings and Division 07 Thermal and Moisture Protection represented the most time-consuming items to review during the submittal evaluation process due to the technical drawings, testing, and installation process involved. Division 04 Masonry therefore did not fall within all of the predefined criticality parameters. There was almost total agreement that aesthetic and architectural building features are included in Division 09 Finishes and that no direct link exists between the finishes and the overall performance of a building.

Following the interviews, as a means of determining the submittal considered to be the most critical, practitioners were requested to rank numerically the five most frequent submittals with respect to how closely they matched the criticality indicators (i.e., number 1 was used to rank the item with the most criticality aspects). The results of the ranking task are presented in Table 3-2.

Table 3-2: Ranking of the Top Five Architectural Submittals

Top Architectural Divisions	UQU	Parsons	RSA	Final Ranking
	Arch. A	Eng. S	Arch. L	
Division 04 Masonry	2	1	2	2
Division 08 Openings	1	2	1	**1** ✔
Division 07 Thermal and Moisture Protection	3	4	4	4
Division 09 Finishes	2	3	3	3
Division 03 Concrete	5	5	5	5

Although the initial analysis with respect to number of submittals showed Division 08 Openings as second, as shown in Figure 3-4, practitioners ranked it as the most critical architectural submittal based on the criticality measures. After the completion of further detailed analysis, the practitioners agreed that architectural windows constitute the most critical of the items included in Division 08 Openings and that this element requires comprehensive decision support for submittal evaluation.

Since architectural windows were identified as the most critical submittals, practical evaluation criteria were required for these items. While some technical criteria had been determined from the specifications collected, additional interviews with the practitioners were conducted in order to identify other windows-related criteria. Descriptions and the significance of some of these evaluation criteria are presented and discussed in the following section.

3.6 Evaluation Criteria for Architectural Windows

Windows constitute a critical item that must be reviewed during the formal submittal evaluation process. The development of the proposed submittal evaluation framework required the acquisition of all windows-related parameters. The specifications collected and the interviews conducted with the practitioners revealed an unsorted list of windows parameters, which are referred to in this study as the evaluation criteria for windows. Table 3-3 lists all of the suggested evaluation criteria.

As shown in Table 3-3, the list includes all aspects of windows that are utilized in a typical windows review and evaluation process. As indicated in Table 3-3, windows can be described according to two means of expression: textual and numerical. While textual expressions, such as colour, style, and material, represent the aesthetic and architectural aspects of windows, numerical expressions refer to the technical factors associated with windows. The textual criteria can be characterized as highly subjective due to their wide ranges of acceptability. On the other hand, technical-related factors are relatively low in subjectivity and limited to a specific range of acceptability.

Table 3-3: Evaluation Criteria for Architectural Windows

Evaluation Criteria for Architectural Windows	Means of Expression	
	Textual	Numerical
Texture	✓	
Style / Section Details	✓	
Openning Style	✓	
Internal Grillls		✓
Glazing	✓	
Uniform Load Deflection		✓
Colour of Frame	✓	
Frame Material	✓	
Visual Transmittance		✓
Tinting	✓	
Coating	✓	
Wind Resistance		✓
Heat Transfer Coefficient		✓
Thermal Movement Control		✓
Air Leakage Control		✓
Water Penetration Control		✓
Noise Control		✓
Forced Entry Control	✓	
Glare Control	✓	
Condensation Resistance		✓
Solar Heat Gain Coefficient		✓
Durability and Sustainability	✓	

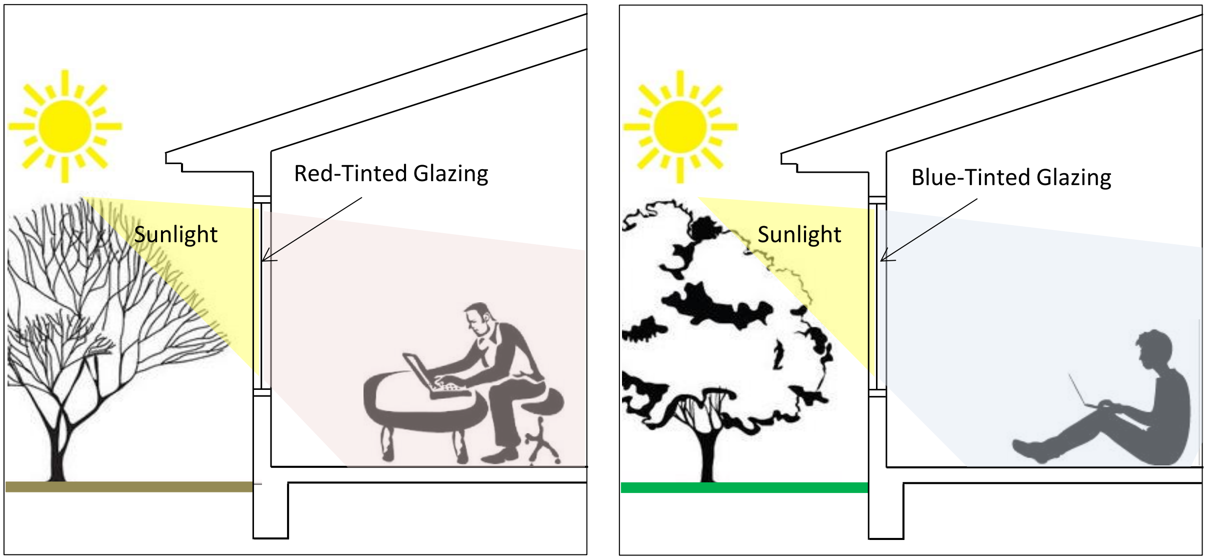
3.6.1 Aesthetic-Related Criteria

The aesthetic and architectural aspects that are expressed as textual criteria represent the primary objective of any project since they are part of the initial conception of a project. In architectural practice, a client describes his/her basic aesthetic requirements for an anticipated building in simple linguistic expressions: a contemporary-style building, a high-tech exterior, a cozy interior space, an environmentally friendly envelope, modern-lifestyle fixtures, a home that feels safe, etc. These unique requirements can be met partly through the establishment of careful specifications for the colours, styles, and materials for the windows. Colour criteria include the colours of the glazing, tinting, and frames. Style criteria cover all opening styles and section details. Material criteria deal with the materials used in the frames and internal grills. While the effects of the technical criteria on the building lifecycle are obvious, the effects of the textual criteria on human behaviour and performance need further explanation. The next sections focus on the subjective criteria associated with windows (i.e., textual criteria); other criteria related to technical specifications are discussed in the next chapter.

Windows, which are factory-glazed and assembled units installed entirely within the exterior wall of a building, provide natural light, ventilation, and visual contact with the outdoor environment. Although these aspects provide the occupants with thermal and visual comfort, the ultimate goal associated with the total experience of windows is the exhilaration of the senses. It is assumed that the physical features of built environments influence the psychological states of users (Vartanian et al. 2013). Physical architectural features such as the façade and height of a building can affect the perceptions and preferences of users (Stamps 1999; Lindal and Hartig 2013). Windows criteria such as colour, style, and material are atmospheric attributes of interior spaces and convey distinctive impressions of both exterior and interior spaces.

Colours: Colour is a complex and powerful phenomenon that can affect human behaviour. People find brighter and more saturated colours more pleasant and appealing (Morgan 1995). Colours that are less bright and saturated tend to be more arousing and to induce feelings of strength, dominance, and boldness in viewers. In general, short-wavelength (cool) colours, such as blue, have been rated the most pleasant. Long-wavelength (warm) colors, such as red, are not perceived to be as pleasant as short-wavelength colours, but are seen as more pleasing than intermediate-wavelength colours. Green seems to be the most arousing. Black has been rated the least pleasant, white the most pleasant, and grays an intermediate level of pleasantness (Morgan 1995). A recent study demonstrated gender sensitivities to colour; females seem more "colour conscious," and their colour tastes appear to be more "flexible and diverse" (Khouw 2012). The effects of colours cannot be ignored; instead, colours should be used effectively as a means of enhancing both the interior and exterior of buildings.

Natural sunlight can be defused into interior spaces via coated-glazed windows. Windows with brown-tinted glazing, for example, diffuse a brownish light into interior spaces, providing an intimate and warm feeling. Spaces in which the occupants need a more energetic attitude can be fitted with windows in arousing tint colours, such as red, green, or yellow (e.g., office buildings). In spaces in which feelings of relaxation and leisure are desired, cool colours such as blues can be a good design choice (e.g., beach houses). Figure 3-5 depicts the effect of the diffusion of sunlight into two interior spaces through colour-tinted glazing.



Space Intended for Energetic Activity   Space Intended for Relaxing Activity

Figure 3-5: Effect of Glazing Colour

As shown in Figure 3-5, colour-glazed windows can enhance interior spaces by defusing natural light and can be proposed by designers as a means of creating particular feelings in the occupants. If the interior spaces are preferred to be neutrally lit, colours can be applied to the exterior face of the glazing to reflect the desired functions of buildings. However, the colours are determined and procured during construction when time is short and decisions are intuitive.

Window frames cover about 20 % to 30 % of the window area. The aesthetic and performance aspects of frames should thus be considered during the architectural design process. The colour of the frames can add architectural value to the building envelope. Frames emphasize the corners/edges of the opening and add a sense of scale to a building façade. A frame colour that contrasts significantly with the exterior cladding can highlight the aesthetic value of the windows by causing them to stand out as separate entities. Figure 3-6 shows the effect of changing the colour of windows frames.

Figure 3-6: Effect of Different Frame Colours

Figure 3-6 shows three identical windows with different frame colours. The selection of colours can be critical due to highly subjective nature. Selecting an item with a colour that differs from that stipulated in the original design can cause inconsistencies with the original intent of the design. For example, if white windows have been designated in order to reflect a contemporary building image, to stand out in a dark textured façade, and to match the interior doors and painting, but for some reason, the project manager has approved dark grey windows, the result will be undesirable. Although the technical aspects have all been satisfied, the design rationale for the choice of colour has not. Selecting an item with the same colour but in a different hue or intensity is an additional factor associated with subjectivity. Failure to clearly document or reference the colour criterion for the windows in the contract documents can increase the opportunity for subjectivity and lead to conflict later on. An efficient and simple method of capturing the subjective aspect of windows and the related design rationale is required in order to facilitate the decision-making process.

Coating: While coated-glazed windows with colour-tinting have been proven to have psychological effects, coated-glazed windows with a low emissivity (low-e) coating are used to provide a light tint that reduces solar transmittance through the glazing. Low-e coatings allow the visible light of the solar spectrum to enter while blocking the other wavelengths that are generally responsible for solar heat gain. These coatings are placed on the inside surface of the outermost pane because most of the solar energy absorbed will dissipate into the ambient air (Sadineni 2011). In cold weather, low-e coatings primarily reduce heat loss by reflecting long-wave heat energy back into the building (Bliss 2006). On the other hand, in hot weather, low-e coatings reflect solar heat energy and reduce heat gain in the building. Figure 3-7 illustrates the effects of low-e coating with respect to the amount of solar heat reflected into the ambient air and the amount absorbed into the building.

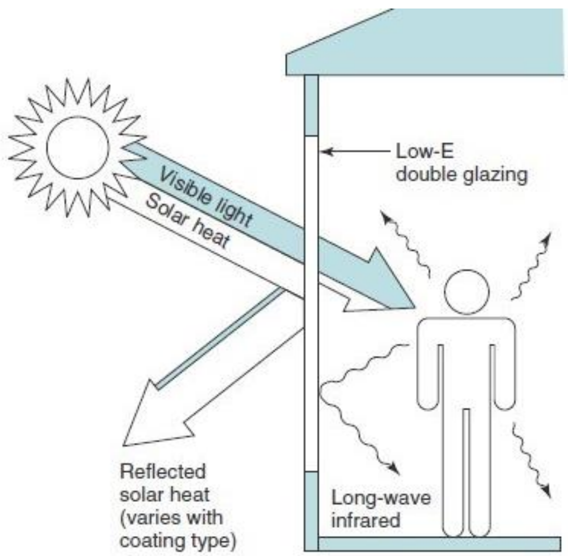


Figure 3-7: Low-E Coatings and Solar Heat Gain (Bliss 2006)

Low-e coatings are of two types: hard coating and soft coating. A hard coating has a tin oxide base whereas a soft coating is usually a thin layer of silver surrounded by dielectric protective layers. Soft silver-based coatings typically entail lower solar transmittance than hard tin-oxide-based coatings. A combination of low-e coatings and noble gas fills the layers in between the glazing, which can increase the centre-of-glass R-values from R6 to R9 (Straube 2010), thus creating high-performance windows with a low heat transfer coefficient (U-value).

Styles: Windows are fabricated in a variety of styles that are suited for different building types and requirements. Styles include the type of window and the patterns resulting from the manner in which the internal grills and simulated divided lites (SDLs) are milled. Windows are available in fixed or operable styles. While the purpose of fixed-style windows is solely for lighting, operable-style windows are designed to direct prevailing winds into the building and to seal the indoors from outdoor environmental conditions. Larger sizes can also be used as emergency exits. Figure 3-8 illustrates common types of windows, their relative tightness, and the amount of natural air that can move through the sashes.

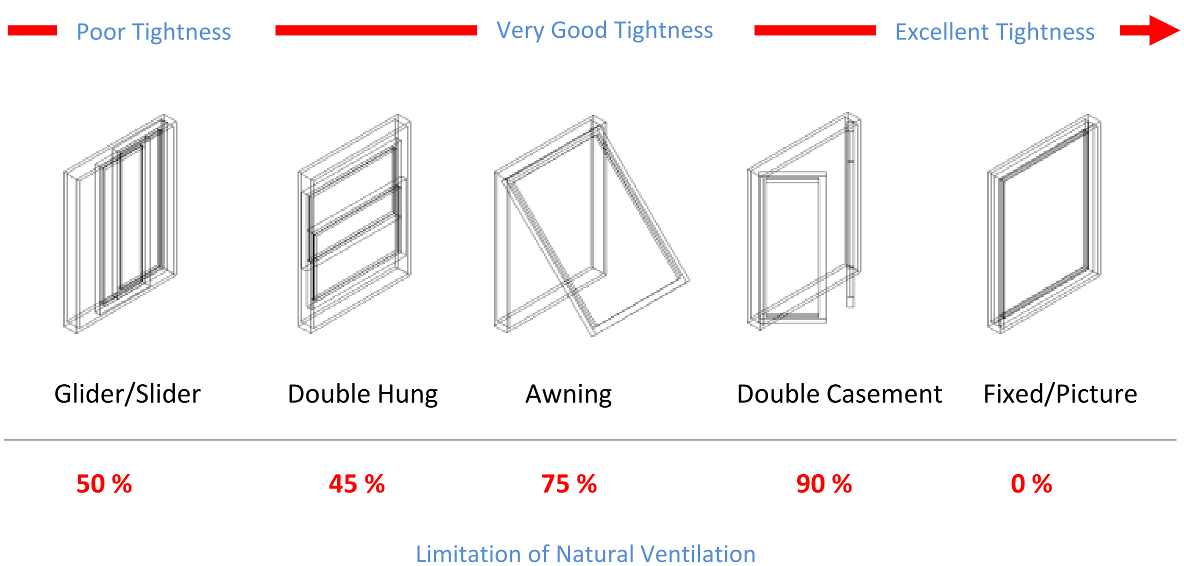


Figure 3-8: Types of Windows and Their Performance with Respect to Tightness

Windows control tightness and natural ventilation. As shown in Figure 3-8, fixed windows are chosen for applications in which maximum tightness is required and natural ventilation is not a priority. Casement-style windows are the best selection for catching fresh breezes due to their opening mechanism. Compression-type windows, such as awning and casement windows, are tighter than slider-type ones. Awning and casement-style windows are therefore preferred in climate zones where rain and winds prevail.

The type of window can contribute to the architectural quality of a space. For example, vertical sliding windows (double hung) represent a style of building that is traditional and affordable while casement-style windows are associated with modern-style buildings. A combination of fixed and operable-style windows reflects a working environment in which the maximum natural light is essential and fresh air is required.

Patterns: The required aesthetic style features can be achieved or ensured through the specification of unique patterns for the internal grills and SDLs. The patterns can include a variety of alignments, materials, and sizes, all of which create specific impressions of the space. Figure 3-9 shows sample internal grill and SDL patterns.

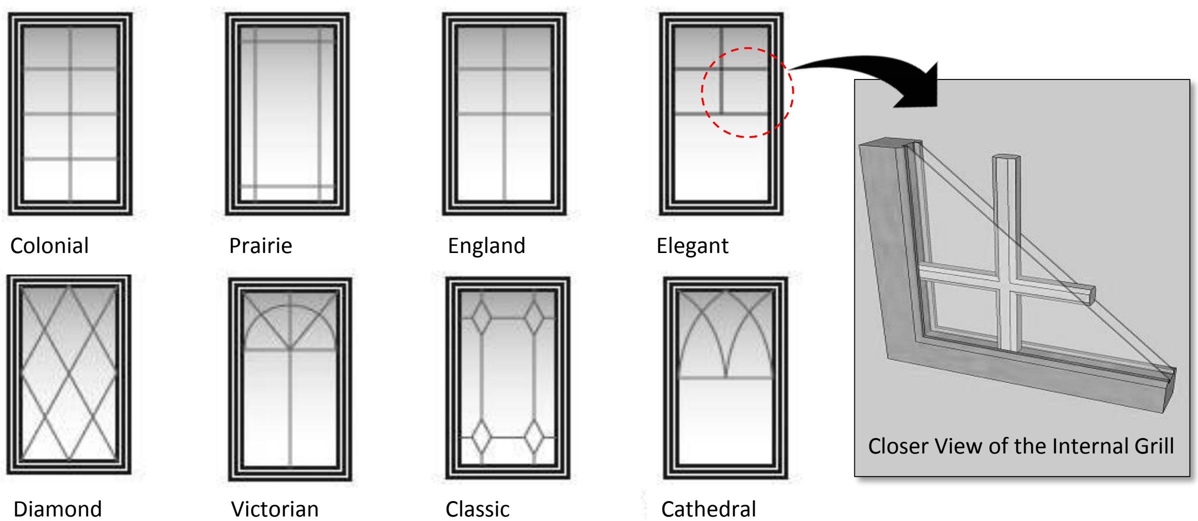


Figure 3-9: Internal Window Grill Patterns and Associated Styles

Each pattern conveys a particular impression to the building occupants. As shown in Figure 3-9, patterns are designed in numerous styles that break up spatial monotony. They may enhance the visual contact between the interior and exterior because they draw focus to the view in between the grills. In double-height walls, patterns can add a horizontal effect to the space to make it feel lower and closer to human scale. In addition to the aesthetic aspects of internal grills, they also play an important role in preventing the glazing panes from rattling and deflecting.

Although window style contributes to both architectural and performance building features, they are described in insufficient detail in drawings and specifications. Instead, they are often generalized and left to be specified during construction, which creates opportunities for subjectivity in their selection. Proper documentation of the intended design of style-related criteria would help project managers avoid approving windows that do not fully meet the aesthetic, activity, and functional requirements for the building.

Material: Window frames are made of either a homogenous or a composite material. Frame materials include aluminum, wood, vinyl, and fiberglass. Because the frames are the most conductive material in windows and a significant amount of heat is lost through them (Straube 2010), the frame material is included as a factor in the determination of the heat transfer coefficient (U-value) of a window.

Window frames have unique characteristics that affect buildings from both an aesthetic and a performance perspective. Wood is the traditional material for residential windows and is suitable for any style or function. Its rich texture conveys historic yet luxurious impressions of the space and seems consistent and friendly with the built environment. When clad with metal or vinyl, wooden windows combine a modern, contemporary style with a traditional, older one. In addition to their aesthetic appeal, wooden windows are an excellent choice for achieving optimum U-values, especially in a cold climate. Whether made with solid wood or clad wood frames, wooden windows have been proven to provide a U-value of 2.00 W/m^{2}.$^{\circ}$K. Table 3-4 lists a variety of window frame materials, the advantages and disadvantages of each material, and their associated U-values.

Table 3-4: Window Frame Materials and their Related U-Values (Bliss 2006)

Frame Material	Advantages	Disadvantages	Whole-Window U-Value* $(W/m^2.K)$	
Aluminum	Light, strong, and durable Neat and crisp sectional details	Poor energy performance (high conductivity)	Frame without thermal break:	**3.4** (0.60)**
			Frame with thermal break:	**2.72** (0.48)
Wood and Clad Wood	Aesthetically appealing Low conductivity Stable in dimension with changes in temperature Strong and rigid Cladded with vinyl, aluminum, or fiberglass	Requires frequent maintenance and painting Vulnerable to decay Shrinks with changes in relative humidity	Wood or clad wood frame:	**2.00** (0.35)
Vinyl	Affordable and high quality Low maintenance Stable in dimension with changes in temperature Excellent insulation value	Limited colour choice (white or beige) Not durable (not manufactured to last forever) Weak material	Typical solid vinyl frame:	**2.00** (0.35)
			Insulated vinyl frame:	**1.53** (0.27)
Fiberglass	Thin and strong for high-tech applications Durable anti-corrosion material Resistent to harsh environmental conditions The most energy efficient frame material	Not widely offered by manufacturers	Fiberglass frame:	**1.53** (0.27)

*Note: U-values for the whole windows of each frame type are based on an average of many windows.

**In parentheses are the U-values in U.S. imperial units (*Btu/h.ft^{2}.F*)

To provide a high-tech image for a building with neat and crisp sectional details, aluminum can be a good choice, but thermal conductivity is a significant issue. As a highly conductive material, aluminum windows at their best (i.e., with a thermal break) can deliver only 2.72 $W/m^2.^{\circ}K$, which is a relatively poor U-value (Table 3-4). During the past decade, the windows fabrication industry has seen the emergence of new materials: vinyl and fiberglass. Solid vinyl windows are popular because they offer high-quality, affordable, low-maintenance frames. The stability of their dimensions with changes in temperature has led to their widespread adoption in cold climates. On the downside, these windows are available in only a few colours, typically white and beige, and they cannot be painted. Fiberglass windows are considered the most resistive to harsh environmental conditions and are thus suitable for hot, humid, or cold weather. In contrast to vinyl, fiberglass windows are applied to high-tech buildings because they are neat and crisp extrusion windows. In terms of performance, fiberglass windows offer the best U-values compared to other materials: 1.53 $W/m^2.^{\circ}K$ (Table 3-4).

The next chapter discusses the categorization and filtering of the evaluation criteria listed in Table 3-3 and explains the separation of textual and technical criteria to be applied in the framework developed for this research.

3.7 Conclusion

This chapter has included an explanation of the data collection process and the identification of the top architectural submittals, which include five items: Division 04 Masonry, Division 08 Openings, Division 07 Thermal and Moisture Protection, Division 09 Finishes, and Division 03 Concrete. According to the criticality measures proposed by experienced practitioners, the Division 08 Openings category satisfies the most measures, and within this division, architectural windows have been determined to constitute the most critical architectural submittals. All of the evaluation criteria related to windows have been listed, and the investigation of the highly subjective aesthetics-related criteria has been described. The results reveal the necessity of including and specifying non-technical (subjective) criteria in the proposed submittal evaluation process. The next chapter discusses the investigation of both textual and technical criteria as they are essential parts of the framework components.

Chapter 4

Submittal Evaluation Criteria

4.1 Introduction

This chapter describes the process of categorizing the evaluation criteria for windows. The complete list of criteria presented in the previous chapter is first divided into two main types: design rationale and performance-related. Design rationale criteria are linguistically based and are identified according to predefined refining measures. Performance-related criteria, which are numerically based, are explained in detail because of their effect on the overall performance of the building. To minimize the subjectivity of decisions derived from performance-related criteria, the analytical hierarchy process (AHP) and multi-attribute utility theory (MAUT) are utilized. The discussion includes an examination of the underlying reasoning for the unique categorization of evaluation criteria and the roles of participating practitioners. Because weights and utility functions are associated with performance-related criteria, they are addressed in detail, including further illustration of the assignment of weights and the generation of utility functions along with in-depth elaboration of the assessment calculations for the U-value and air infiltration criteria.

4.2 Categories of Evaluation Criteria

The individual evaluation criteria associated with windows are interrelated but must be categorized if they are to be useful in the submittal evaluation process. Some non-measurable criteria can lead to highly subjective decisions while the measurement of other criteria involves only a small degree of subjectivity. For the purposes of this study, the evaluation criteria are divided into two categories according to the level of subjectivity and technicality: design rationale criteria and performance-related criteria. The following subsections include descriptions of these criteria, the refinement process, and the method of generating weights and utility functions for each performance-related criterion.

4.2.1 Design Rationale Criteria

Windows are described according to non-measurable criteria that add qualitative value to both the inside and the outside of building enclosures: style, material, and colour. These criteria are usually represented and captured in drawings. The design intent that determines the unique selection of each criterion is established early in the design process and is influenced by the architectural design concepts, location, type of project, owner's preferences, and environmental conditions. As mentioned in the literature, design rationale is a factor that has not yet been documented in any form in drawings or specifications. The evaluation of window submittals is still a visual process based on information extracted/retrieved from drawings and, in the absence of this information, on experience. It is clear that the availability of the design rationale in a convenient documented form during the submittal evaluation process can increase the efficiency of decision-making and the level of user satisfaction.

One objective of this study was the development of a method for clearly identifying and storing design rationale criteria so that they can be available as a major component of the evaluation process. To achieve this goal, the initial list of criteria (Table 3-3) was reviewed and refined based on a filtering/qualitative measure in order to create a list of suggested design rationale criteria for windows. The guidelines for including a criterion in the suggested list were that it must be expressed linguistically with no specific numerical preference value and that it must be associated with a wide range of acceptability (e.g., clear glass, new style, brightly coloured frame, acceptable transparency level, certified windows, etc.). The criterion must also represent a contribution to the architectural style of the building (e.g., modern, historic, traditional, etc.) and an enhancement of the indoor environment (e.g., cozy spaces, intimate rooms, etc.). These qualities can be delivered through the control of natural lighting and ventilation by means of tinting, coating, and choice of window type and through evidence of reliability, such as compliance with certified national standards.

After discussion with participating practitioners, a list was compiled of eleven criteria that were consistent with the filtering measures, and a final list was then proposed based on the top criteria preferred by the practitioners. Table 4-1 shows the suggested and refined list of design rationale criteria.

Table 4-1: Suggested and Refined Lists of Design Rationale Criteria

Suggested List of Design Rationale Criteria	Feedback from Participating Practitioners			Refined List of Design Rationale Criteria
	UQU	Parsons	RSA	
	Arch. A	Eng. S	Arch. L	
Details and Accessories	✓	✓		
Frame Material	✓	✓	✓	**Frame Material**
Glare Control	✓	✓		
Style	✓	✓	✓	**Style**
Colour	✓	✓	✓	**Colour**
Glazing	✓	✓	✓	**Glazing**
Texture		✓		
Tinting	✓	✓	✓	**Tinting**
Coating			✓	
CSA Compliance	✓	✓	✓	**CSA Compliance**
Energy Star Certified	✓	✓	✓	**Energy Star Certified**

The final list, as refined by the practitioners, consists of seven design rationale criteria: frame material, style, colour, glazing, tinting, Canadian Standards Association (CSA) compliance, and Energy Star Certification. The refined list includes parameters used to describe both the aesthetic and architectural aspects of windows.

These design rationale criteria should be conveniently documented for use during the windows evaluation process. The frame material criterion relates to the selection of a framing material that is consistent with the desired architectural style and that also offers optimum durability and thermal conductivity. The style criterion indicates the type of window (i.e., single slider, double/single hung, awning, casement, etc.) and the arrangement of decorative patterns, such as internal grills and simulated divided lites (SDLs). In this context, the style criterion is associated with the regulation of the amount of natural light and ventilation required in the interior spaces: residential buildings require specific window types and patterns that might not be utilized in commercial office buildings or recreational facilities.

The colour criterion refers to the documentation/capture of interior and exterior window frames so that they align with the architectural design concept and reflect the function of the building. The glazing criterion is associated with the number of layers of glazing, such as single, double, or triple; the addition of a low-emissivity (Low-E) coating; and the types of filler used, such as argon, krypton, or xenon. The design rationale criterion that denotes the control of glare and glazing colour is listed as a tinting criterion in the refined list. Tinting and coating are the primary factors that affect the reflection of unwanted (passive) heat and that control the amount of light and heat transmitted through the glazing, thus enhancing thermal comfort and providing the required illumination of the space.

The inclusion of the CSA compliance criterion ensures that the quality and sustainability of the windows meet nationally reliable Canadian standards. Although CSA rating labels are limited to an assurance that the windows tested meet technical criteria, they also imply a high standard of quality with respect to the overall window assembly, including frame materials, colour, frame structure, and glazing (i.e., the design rationale criteria for this research).

ENERGY STAR® is a program administered by Natural Resources Canada (NRCAN) to help identify the most energy-efficient products. For a window to carry the Energy Star label, it must meet or exceed the efficiency guidelines set by NRCAN. The Energy Rating (ER) is simply an indicator of the efficiency of the entire window unit and is given in unitless numbers that range from zero (poorest rating) to about 50 (excellent performance). The ER is not a temperature rating but is rather a scale for rating the comparative performance of windows based on the U-value (thermal movement through window components), the solar heat gain, and the air leakage rate (RDH 2013). Rating numbers can be referenced to the specific climate zone where the windows are installed. For example, Ontario is assigned to a climate zone for which the minimum acceptable energy rating is 29. Installing windows with an appropriate Energy Star rating is essential for meeting the climate specifications for each zone. The design rationale criteria are meant to be used as a component of the complete process for evaluating window submittals. To conform to the qualitative nature of such criteria, they must be expressed in a textual checklist format. The effective application of the design rationale criteria in the submittal evaluation process is explained in Chapter 5.

4.2.2 Performance-Related Criteria

Considered sophisticated elements of buildings, windows can affect the overall building performance. In specifications, windows are described according to their required performance level. This subsection identifies the performance-related criteria for windows that were included in the initial list shown in Table 3-3. The assignment of weights and the generation of utility functions for each performance-related criterion are explained. The CSA-A440 performance standard for windows (CSA 2006) and practitioner feedback are the references used in this aspect of the research. The creation of an initial list of performance-related criteria was based on adherence to the filtering measures. For a criterion to be included in the list, it must be described in numerical (quantitative) values within a limited range of acceptability and must represent a factor that affects the overall performance of the building enclosure. Table 4-2 shows the suggested list of performance-related criteria and the refined list based on the practitioner feedback.

Table 4-2: Identified Performance-Related Criteria

Suggested List of Performance-Related Criteria	**Feedback from Participating Practitioners**			**Refined List of Performance-Related Criteria**
	UQU	**Parsons**	**RSA**	
	Arch. A	Eng. S	Arch. L	
U-Value	✓	✓	✓	**U-Value**
Section Details	✓			
Air Infiltration	✓	✓	✓	**Air Infiltration**
Water Penetration	✓	✓	✓	**Water Penetration**
Wind Resistance	✓	✓		
Acoustic Level	✓		✓	
Visible Tansmittance (VT)	✓	✓	✓	**Visible Transmittance (VT)**
Condensation Resistance			✓	
Resistance to Forced Entry		✓		
Solar Heat Gain Coefficient (SHGC)	✓	✓	✓	**Solar Heat Gain Coefficient (SHGC)**

The refined list of performance-related criteria, as shown in Table 4-2, covers the aspects of windows that control thermal transmittance, facilitate human comfort, and ensure the quality of the indoor environment: the U-value, air infiltration, water penetration, visible transmittance (VT), and solar heat gain coefficient (SHGC). These aspects are also included in CSA standardized testing procedures and rating systems associated with the CSA-A440-00 performance standard for windows (CSA 2006). For every window unit, the fabricator provides a label that lists the mandatory ratings for labeling CSA-certified products: the U-value, VT, and SHGC. Air infiltration and water penetration are supplementary ratings that are provided as required for meeting project specifications.

The window label also includes non-performance aspects of windows such as wind load resistance (C3), insect screen strength (S1), and resistance to forced entry (F2). Basic architectural features that are already included in the final list of design rationale criteria are described as well, including opening style, material, glazing, and grill size. However, the information provided on the label is based on the level of specification detail. Rough specifications or lack of specification data affect the amount of information included on the label and therefore the quality of the final product. Figure 4-1 shows a sample CSA label for a window that has been certified in Canada. In the United States, the National Fenestration Rating Council (NFRC) establishes equivalent standards for certified window-rating labels.

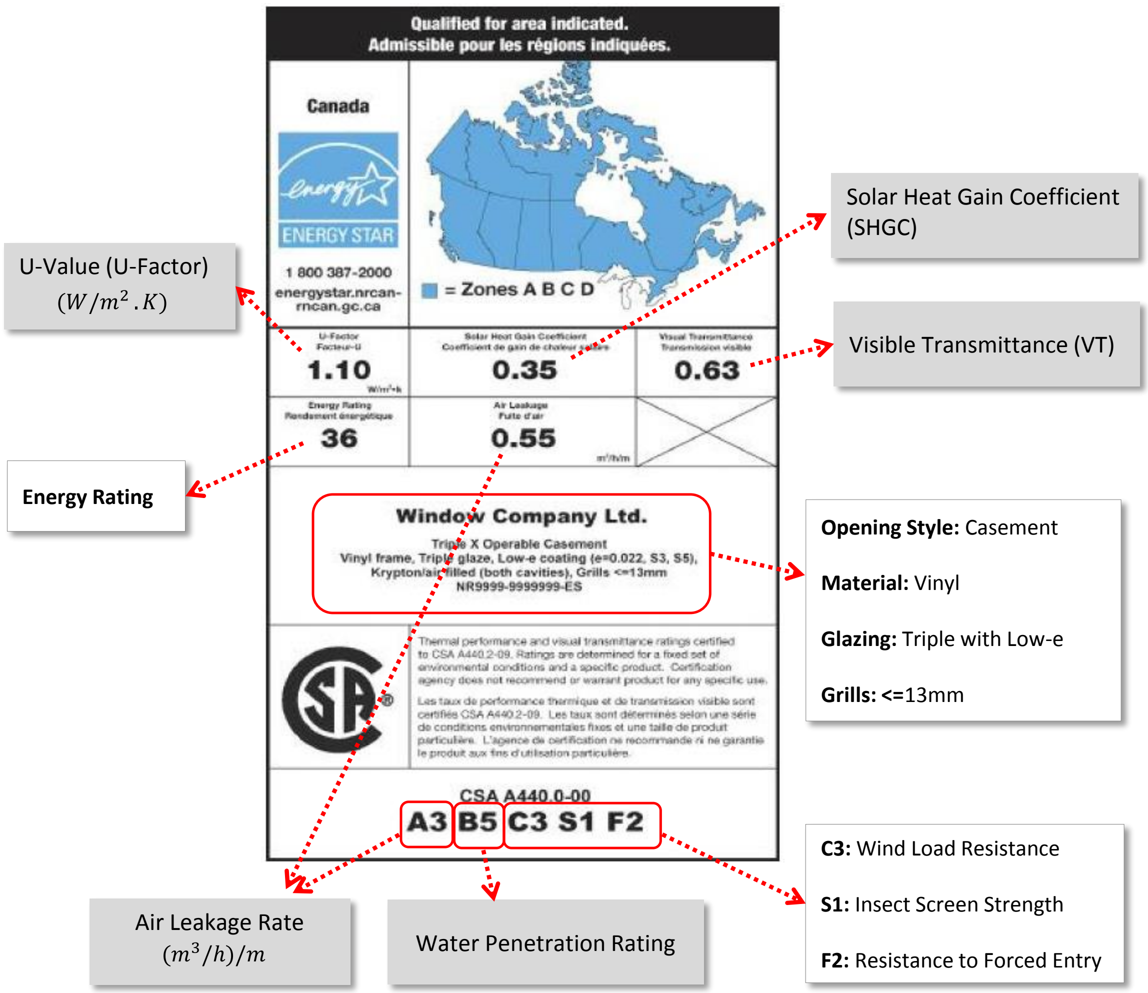


Figure 4-1: Sample Window Label with a Map of Canada (NRCAN 2011b)

For the research conducted for this thesis, the performance-related criteria are intended to be an essential component of the process for evaluating window submittals. The evaluation of such criteria requires a structured mechanism that can reduce subjectivity and enhance the efficiency of decisions. The quantitative measurement of these criteria requires the calculation of an overall score, which can be achieved through the assignment of weights and utility functions for the criteria. For this research, the weights are generated by means of the analytical hierarchy process (AHP), and the utility functions are developed using multi-attribute utility theory (MAUT).

AHP Weights: weights are determined from the reconciliation of a pairwise comparison matrix of the importance of the criteria relative to a 1-9 numerical ratio scale of comparisons (Saaty 1980). The suggested scale of comparisons is shown in Table 4-3. If criterion *i* is preferred over criterion *j*, then element (*i*,*j*) of the matrix is the strength of the preference for *i* over *j*. Element (*j*,*i*) therefore becomes the inverse of that number. Sample weight calculations for performance-related criteria that are calculated based on feedback from a data source (UQU) are available in Appendix B.

Table 4-3: Scale of Comparisons for the AHP (Saaty 1980)

Scale of Comparisons for the AHP	
1	Equal Importance / Equal Preference
3	Moderate Importance / Weak Preference
5	Essential Importance / Strong Preference
7	Very Strong Importance / Demonstrable Preference
9	Extreme Importance / Absolute Preference
2,4,6,8	Intermediate Levels

For the assignment of weights for each performance-related criterion, a pairwise matrix was developed. Practitioners were asked to compare all criteria with respect to one another according to their own preferences. After their assessments were obtained, weights were calculated and consistencies were checked. A final weight was then assigned to each criterion so that the sum would equal 1.0. Table 4-4 summarizes the final weights according to the participating practitioners' opinion of the predefined performance-related criteria.

Table 4-4: Final Weights Assigned to Performance-Related Criteria

Performance-Related Criteria	UQU	Parsons	RSA	Final Weights
	arch. M	eng. S	arch. X	
U-Value	0.46	0.50	0.52	**0.49**
Air Infiltration	0.22	0.21	0.20	**0.21**
Water Penetration	0.14	0.13	0.11	**0.13**
Visible Transmittance (VT)	0.06	0.05	0.04	**0.05**
Solar Heat Gain Coefficient (SHGC)	0.13	0.10	0.12	**0.12**

The final weights shown in Table 4-4 have been assigned for each criterion based on the average of the weights provided by the practitioners from each organization. The practitioners allocated almost identical weights because windows perform similarly in cold or hot climate conditions. The hierarchy of the weights initially indicates the criticality of each criterion with respect to the performance of a window assembly. At this stage, it is assumed that minor changes in a heavily weighted windows criterion during the submittal process can have a negative effect on overall building performance. The Table 4-4 list of final weights indicates that the U-value and air infiltration have been assigned the highest weights of 0.49 and 0.21, respectively, and that VT has been assigned the lowest: 0.05.

MAUT: Since the contractor might submit window options with minor differences from the original specifications, MAUT is utilized as a means of establishing a quantitative measure (score) that represents any minor deviation in submittals with respect to performance-related criteria. The score for each criterion j is the weight W_j multiplied by the utility value U_j. The overall score for submittal i, X_i, is the sum of all scores and is given by

$$X_i = \sum_{i=1}^{n} W_j \, U_j \qquad\qquad i = 1,2,3,\ldots,n \tag{4-1}$$

The generation of a utility function for each performance-related criterion requires the definition of the range of acceptability for that criterion. The range comprises several alternatives that are set based on performance standards and organizational constraints. These alternatives create a number of intervals that determine the shape of the utility functions that are developed: risk-seeking, risk-averse, or risk-indifferent. The default is always a risk-indifferent curve. During the early stages of the project or even prior to the beginning of construction, the utility value for each alternative within the acceptability range is determined by the practitioners based on their preferences or level of satisfaction. Pre-modeling such preferences using MAUT facilitates timely, automated decisions that involve a minimum amount of subjectivity.

For the development of the utility functions, the ranges of acceptability and intervals were set up based on the interview and survey results. The minimization of data collection problems and practitioner bias was an important consideration during this task. Data collection problems and judgments based on inherited bias have been discussed under several research headings: myside bias, the recency effect, the Von Restorff effect, the collective unconscious, the contrast effect, and dominance.

4.2.2.1 U-Value: Heat Transfer Coefficient

Energy consumption is a global concern. According to the United Nations Environment Programme (UNEP), buildings account for up to 40 % of all primary energy use, greenhouse gas emissions, and waste generation (UNEP 2007). Windows are a major source of energy loss in building enclosures and are the weakest thermal bridge in buildings characterized by high levels of thermal conductivity. Significant heat (20 % to 40 %) is lost from buildings through the highly conductive glazed sections of the envelope: windows (Bulow-Hube 2001; Grynning et al. 2013). By nature, heat tends to move from warm to cold environments. Whether it flows from warmer interiors to cooler exteriors during winter, or in the reverse direction in summer, heat is transferred through the building envelope via three modes: conduction, convection, and radiation (Carmody 2004; Straube 2010). Conduction is defined as heat transferring through a material, and convection refers to the transfer of heat through the movement of the molecules of a fluid (air). Conduction occurs when two objects are in direct contact (e.g., air against a window). In buildings, heat loss by convection occurs primarily through infiltration: the introduction of outside cold air into the building through building cracks (e.g., around window gaskets and sills). Radiation is the transfer of heat by means of electromagnetic waves. All three means of heat transfer occur through and around windows, as illustrated in Figure 4-2.

The standard method of quantifying the overall heat transfer through a window assembly is the U-value. Also referred to as the total heat transfer coefficient, the U-value represents the rate of heat flow/transfer (in Watts or Btu per hour) through windows per unit area and per temperature difference between the indoor and outdoor air ($W/m^2.^{\circ}K$ or $Btu/h.ft^2.^{\circ}F$). The U-value is the reciprocal of the insulating value (R-value) of a material. Thus, the lower the U-value of a window unit, the less heat is transferred (wasted/lost) outward in winter and inward in summer.

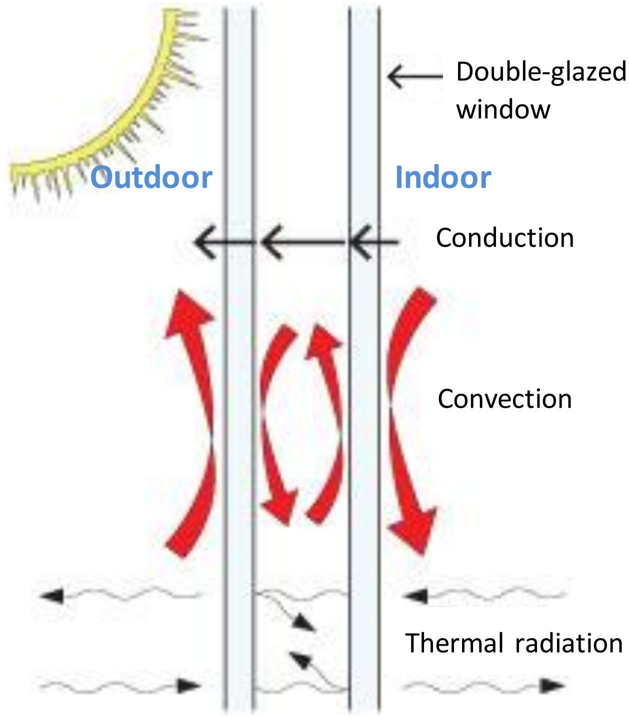


Figure 4-2: Modes of Heat Transfer through a Window (Carmody 2004)

Windows are a composite of a number of assemblies that affect their overall performance. The U-value of a window unit is expressed in two ways: the centre-of-glass U-value and the U-value of the total window assembly (Carmody 2004). While the former is affected by the layers of glazing, filling, and coating, the latter is affected by the glazing characteristics, the frame, and the window sash. The U-value of the entire window unit is the most comprehensive and incorporates default energy ratings that indicate window performance (NRCAN 2011b; NFRC 2013). Therefore, for the purposes of this research, the amount of heat loss through the entire window unit has been used as the standard for evaluating window submittals.

In Canada, the U-values required for windows are determined based on the Energy Rating (ER) calculation as defined by the CSA. According to NRCAN, Canada is divided into four thermal zones: A, B, C, and D, with zone A being the warmest. Most of Ontario is in a colder zone, C, for which the optimum U-value for windows is set at 1.4 $W/m^2.^{\circ}K$ (0.25 $Btu/h.ft^2.^{\circ}F$) and the maximum acceptable U-value is 2.0 $W/m^2.^{\circ}K$ (0.35 $Btu/h.ft^2.^{\circ}F$) (NRCAN 2011b). Appendix C includes the zoning map, ER ratings, and acceptable U-values for windows according to NRCAN (2011b).

The overall U-value of windows can be six times greater than that of other building components such as walls, doors, and the roof. In a highly insulated building with a window-to-wall ratio (WWR) of 0.45, as with the example described in Table 4-5, windows with a best-attained U-value (i.e., 1.4 $W/m^2.^{\circ}K$) that cover 45 % of surface wall areas comprise about 76.3 % of the thermal load, which is significant compared to the 14 % thermal load contribution of walls. In other words, the performance of windows with the best U-values is still substantially poorer than that of a typical wall. Increasing the U-value of the windows, which is a typical submittal scenario, will lead to higher thermal conductivity (U*A Factor) of the windows, which in turn, means that they represent a greater proportion of the thermal load: 82.2 % at 2.0 $W/m^2.^{\circ}K$, which is the maximum acceptable U-value.

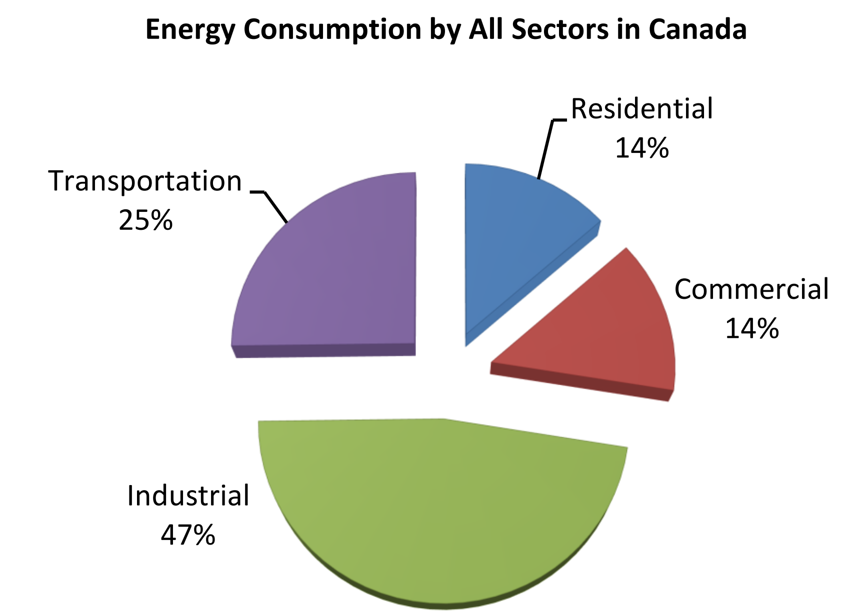
Table 4-5: Effect of the Thermal Load of Windows on a Building

WWR: 0.45				
Total Surface Area (Walls, Windows, Roof): 4,800 m^2				
Building Component	U-value $(W/m^2.K)$	Surface Area (m^2)	U*A Factor (W/K)	Thermal Load on Building
Walls	0.21	2200 (55%)	462	**14.0%**
Windows	1.40	1800 (45%)	2520	**76.3%**
Roof	0.40	800	320	**9.7%**

In cold climates, such as Canada, the northern U.S. states, and some European and Asian countries, a significant amount of energy is consumed by heating indoor environments so that they provide optimum thermal comfort. A survey conducted in two major Chinese cities showed that 60 % of the total heat loss is due to windows and doors (Yang et al. 2004). A Norwegian study concluded that building stock demanded an amount of energy equal to approximately 40 % of all energy consumption (Sartori 2008).

In the U.S., approximately 11.7 trillion kWh, which represents approximately 41 % of total energy, is consumed by residential and commercial buildings (U.S. DOE 2012); half of this consumption is used for heating. Buildings sector in the U.S., which consists of 85 million existing residential and commercial buildings, are expected to grow significantly every year: 1 million buildings each year. The number of buildings is projected to grow to over $ 100 million by 2035 (U.S. DOE 2010). The significant amount of energy that is consumed by these buildings must be rationalized and considered, specially knowing that the cost of operation is much exhausted than the cost of initial design and construction. Efforts are directed to reduce energy use in U.S. buildings. For instance, the U.S. Department of Energy (DOE) has set a goal to reduce building energy consumption in commercial buildings by 20 % by 2020 (Stephens 2013).

Statistics recently released by the Natural Energy Board (NEB) of Canada and Natural Resources Canada (NRCAN) reveal that approximately 28 % of the total energy used in 2010 was consumed by residential and commercial buildings, with approximately 63 % used for heating residential spaces (NEB 2012; NRCAN 2011a). A further factor is the load represented by the additional energy requirements associated with the enormous amount of new construction: $154 billion in 2004, projected to expand to $300 billion in 2014 (Carrick 2011). Figure 4-3 shows the distribution of Canadian energy consumption by all sectors and for residential end-use.



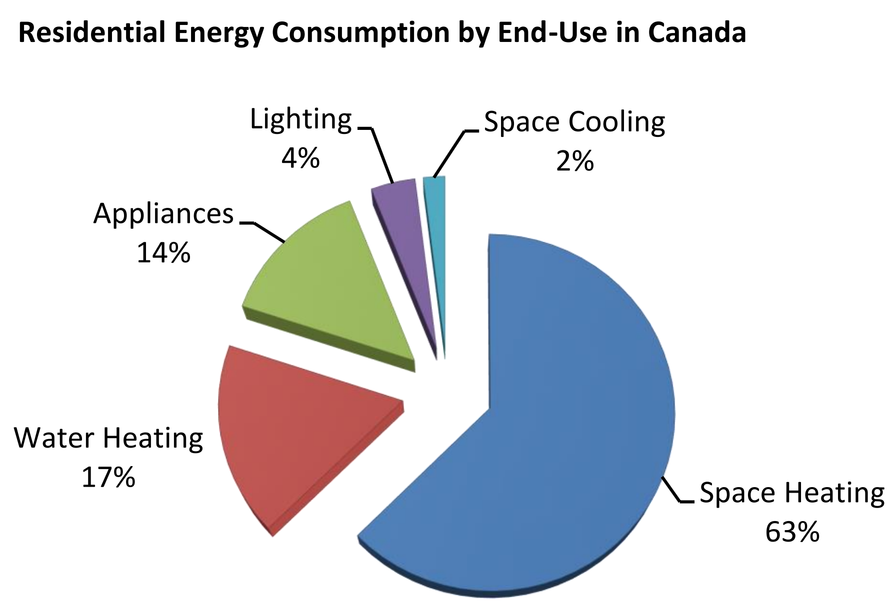


Figure 4-3: Distribution of Energy Consumption in Canada (NEB 2012; NRCAN 2011a)

Because of the significance of the effect of the U-value of the windows on the overall energy consumption of a building, the U-value is a major factor in heat loss calculations. The heat flow rate Q through a component j with a U-value U_j and a surface area A_j is given by

$$Q_j = U_j \times A_j \times (T_{in} - T_{out}) \tag{4-2}$$

where

Q_j is the heat flow rate (heat loss), in watts;

U_j is the heat transfer coefficient (U-value), in $W/m^2.^{\circ}K$;

A_j is the surface area of the components, in m^2;

T_{in} is the inside temperature, in $^{\circ}C$;

T_{out} is the outside temperature, in $^{\circ}C$.

Equation 4-2 gives the heat flow rate in watts (i.e., joule per second) which represents the rate at which energy is transferred or absorbed over units of time. The energy consumption of a building is typically measured according to the amount of power (kilowatts) expended over time (hour). A kilowatt-hour (kWh) thus becomes the unit that indicates the amount of energy required to heat or cool a building over a specific period of time (daily, monthly, or annually). In practice, buildings are exposed to a variety of environmental conditions throughout the year. The difference between inside and outside temperatures fluctuates and is thus neither constant nor stable. For this reason, the concept of degree-days (DDs) has been adopted for this research.

DDs represent the summation of temperature differences over time. In this context, temperature difference refers to the discrepancy between a reference temperature (base temperature) and the outdoor air temperature (CIBSE 2006). DDs indicate the amount of heat energy required to maintain a constant indoor air temperature, for example, a base temperature of 15 °C, as outdoor temperatures fluctuate. Distinguishing heating degree-days (HDDs) and cooling degree-days (CDDs) is a simple method of characterizing the severity of a particular climate (ASHRAE 2009). The number of HDDs is greater in colder climates since more heat energy is required to maintain a constant indoor temperature. In the same way, the number of CDDs is used as an indicator of the amount of cooling energy required in order to maintain an indoor air temperature at a base temperature when the outdoor temperature is unstable. CDDs are commonly used in countries with warm climates because most of the energy is consumed for cooling. Appendix D shows examples of HDDs and CDDs utilized in this study for a base temperature of 15 $^{\circ}$C.

The annual amount of energy consumed for heating due to heat loss (conduction) through basic building components including walls, windows, and the roof is given by the following calculation (based on Sherman 1986; CIBSE 2006):

$$Q_{heating} = (U \times A \times HDD)(24 \div 1000) \quad (4\text{-}3)$$

where

$Q_{heating}$ is the annual amount of energy consumption used for heating, in Kwh;

U is the U-value for building surface areas including walls, windows, and the roof, in W/m^2.$^{\circ}$K;

A is the total surface areas for walls, windows, and the roof, in m^2;

HDD is the number of heating degree-days, in $^{\circ}$C-days.

It should be noted that 24 hours is included as a means of converting from days to hours.

The cost of the annual energy consumption used for heating is given by

$$E_{heating} = Q_{heating} \times P_g \tag{4-4}$$

where

$E_{heating}$ is the cost of energy consumption used for heating, in dollars;

P_{gas} is the monthly price of natural gas [0.022 $/kWh].

Likewise, the annual energy consumed for cooling can be calculated by

$$Q_{cooling} = (U \times A \times CDD)(24 \div 1000) \tag{4-5}$$

where

$Q_{cooling}$ is the annual amount of energy consumption used for cooling, in kWh;

CDD is the number of cooling degree-days, in $^{\circ}$C-days.

The cost of the annual energy consumption used for cooling is given by

$$E_{cooling} = Q_{cooling} \times P_e \tag{4-6}$$

where

$E_{cooling}$ is the cost of energy consumption used for cooling, in dollars;

P_e is the monthly price of electricity [0.09 $/kWh].

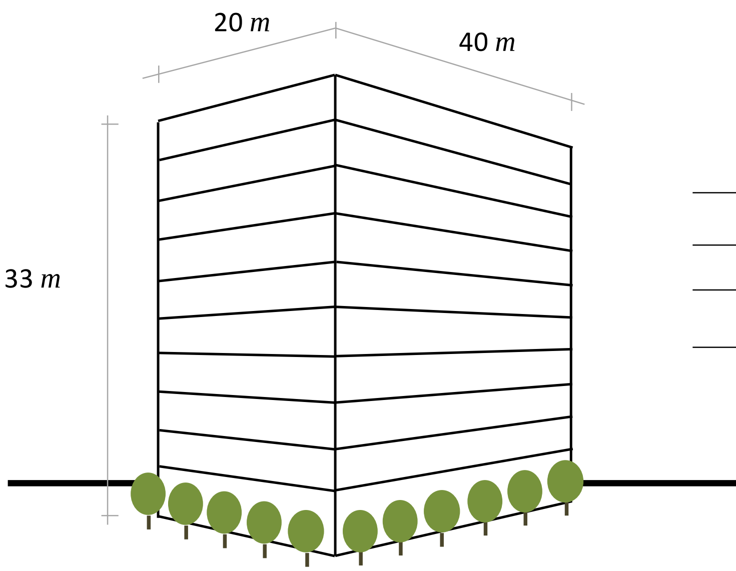
The overall energy consumption, in kWh, for heating and cooling is given by

$$Q_{total} = Q_{heating} + Q_{cooling} \tag{4-7}$$

The final calculation is the overall cost of energy consumption, in dollars, for heating and cooling:

$$E_{total} = E_{heating} + E_{cooling} \tag{4-8}$$

To show how a slight change in the U-value of the windows can affect the overall energy consumption of a building, an analysis is presented for a sample basic building. For example, a ten-story building located in Toronto (HDDs are 3279 and CDDs are 623 $^{\circ}$C-days) has a roof area of 800 m^2 and walls of approximately 4,000 m^2, including windows, as illustrated in Figure 4-4.



Surface Areas	
Roof	Walls
800 m^2	4,000 m^2

Figure 4-4: Sample Building for U-Value Analysis

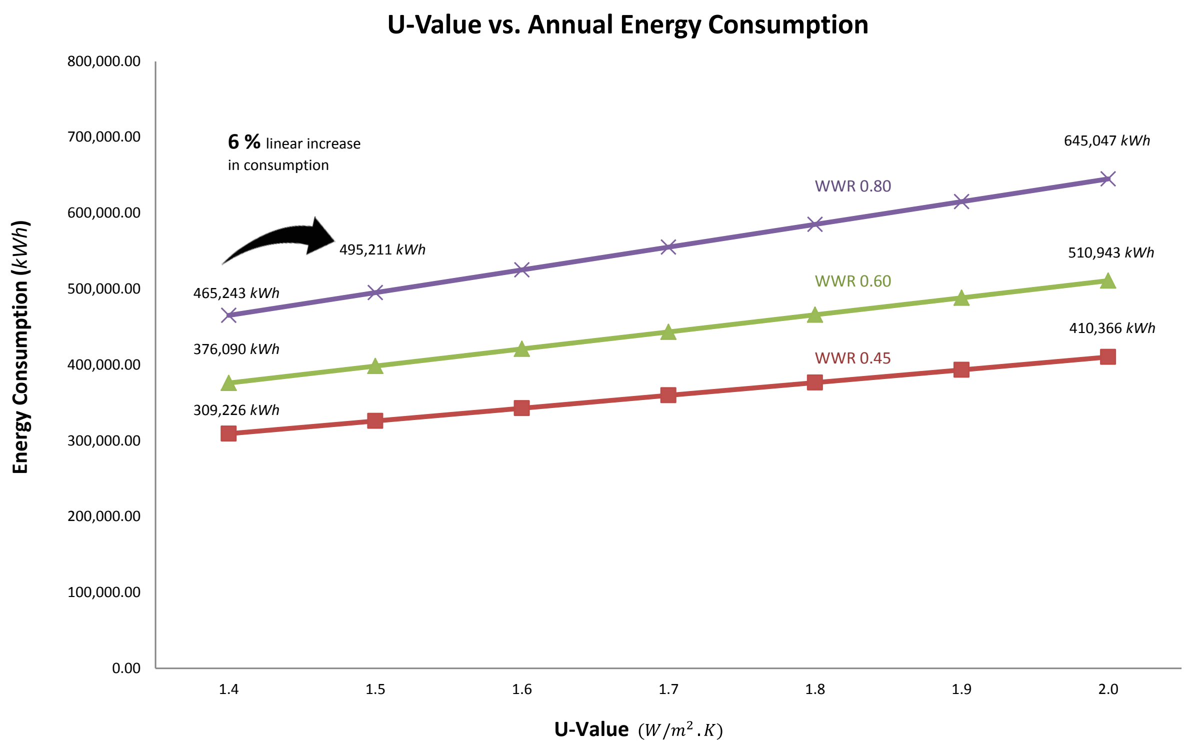
The window-to-wall ratio (WWR) of the entire envelope is assumed to vary, with values of 0.45, 0.60, and 0.80. For the purposes of this sample analysis, the U-values of the walls and roof are assumed to be constant at 0.21 $W/m^2.^{\circ}K$ and 0.40 $W/m^2.^{\circ}K$, respectively. The effects of gradual changes in the U-values of windows on the annual energy consumption (Q_{total}) and the cost of the annual energy consumption (E_{total}) of the sample building are indicated in Table 4-6.

Table 4-6: Effect on Overall Energy Consumption of Changes in the U-Values of the Windows

U-Value of Windows $(W/m^2.K)$	WWR		WWR		WWR	
	0.45		0.60		0.80	
	Surface Area (m^2)		Surface Area (m^2)		Surface Area (m^2)	
	Walls / *Windows* / *Roof*		*Walls* / *Windows* / *Roof*		*Walls* / *Windows* / *Roof*	
	2200 / 1800 / 800		1600 / 2400 / 800		800 / 3200 / 800	
	Q_{total} * (kWh)	E_{total} ** $(\$)$	Q_{total} (kWh)	E_{total} $(\$)$	Q_{total} (kWh)	E_{total} $(\$)$
1.4	309,226	$10,160	376,090	$12,357	465,243	$15,286
1.5	326,082	$10,714	398,566	$13,096	495,211	$16,271
1.6	342,939	$11,268	421,041	$13,834	525,178	$17,256
1.7	359,796	$11,822	443,517	$14,573	555,145	$18,240
1.8	376,652	$12,376	465,992	$15,311	585,113	$19,225
1.9	393,509	$12,930	488,468	$16,050	615,080	$20,210
2.0	410,366	$13,483	510,943	$16,788	645,047	$21,194

* Based on eq. (4-7)
** Based on eq. (4-8)

Table 4-6 includes data for three scenarios of expected changes in the WWR of the building. The changes in the U-values and the implied consequences with respect to overall energy consumption are summarized for further analysis. A plotted graph of the information from Table 4-6 is presented in Figure 4-5.



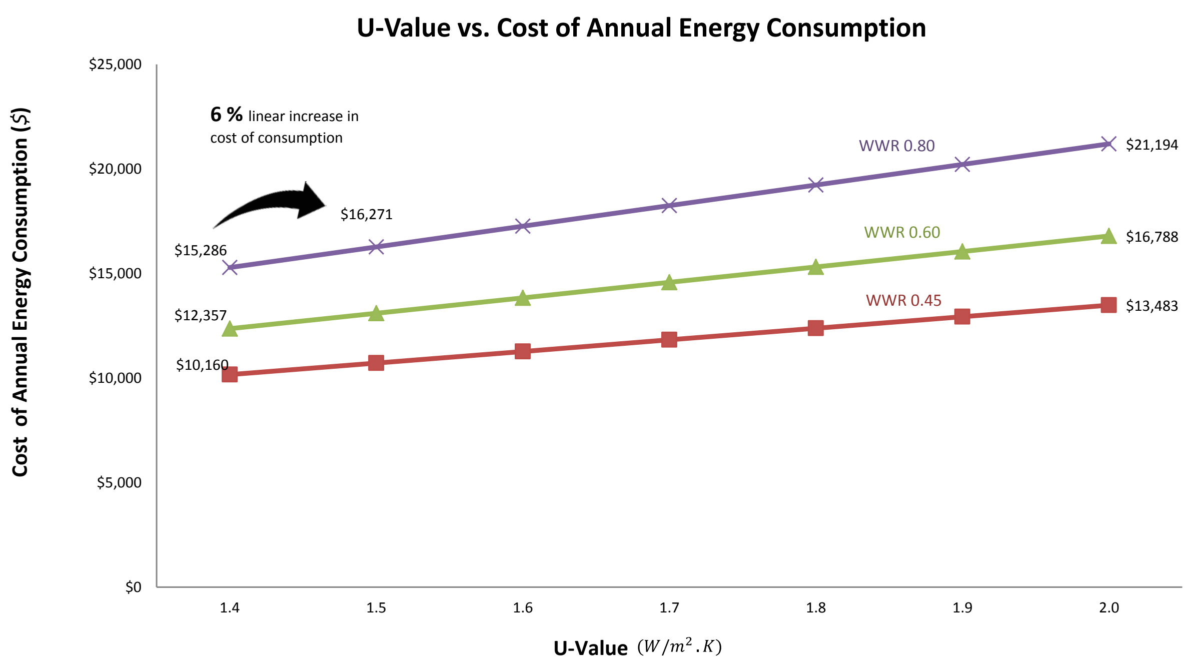


Figure 4-5: Effects on Overall Annual Energy Consumption of Changes in the U-Value

Energy consumption is highly dependent on the WWR of the building envelope. A building with a WWR of 0.45, as shown in Table 4-6 and Figure 4-5, consumes approximately 309,226 kWh of energy annually (approximately $10,160) at a 1.4 U-value. However, the same building with a different WWR (e.g., 0.80) consumes more energy at the same U-value: approximately 465,243 kWh of energy, costing approximately $15,286: a 33.5 % difference. The greater the WWR, the more the bulk of the thermal conductivity (the U*A factor) is shifted toward the windows, with correspondingly more energy being lost through them.

An analysis of the example provided shows that energy consumption increases consistently with any minor change in the U-value of the windows. If the WWR is 0.80, the annual consumption can increase by up to 6 % for a submittal that includes a minor window change (e.g., from 1.4 $W/m^2.^{\circ}K$ to 1.5 $W/m^2.^{\circ}K$), which entails an annual cost difference of $985. This difference affects the operational aspects of a building and imposes an extra energy cost that can add up to approximately $8,399 after 10 years at a 3 % interest rate. When the submittal contains a window with the least acceptable U-value of 2.0 $W/m^2.^{\circ}K$, the difference in consumption and cost increases significantly: up to approximately 28 %, which translates into 179,804 kWh and $5,908, respectively. If such a change scenario occurs during the submittal evaluation process, it could lead to a long-term cost of approximately $50,395 after 10 years at a 3 % interest rate, or $87,894 after 20 years at the same interest rate. The long-term implications resulting from deviations in the submitted U-value of windows should thus be taken into consideration with respect to operational compensation (or savings in the cost of consumption) before the approval of such a window. In summary, the long-term performance of a building is affected by slight changes in the U-value of its windows. Consideration of the operational implications of the U-value criterion was therefore included in the development of the framework created for this thesis.

Inclusion of the U-value criterion in the submittal evaluation process required the generation of utility functions for quantifying the practitioners' preferences. Table 4-7 shows the acceptable range for the U-value criterion as well as the utility values suggested by each practitioner and the average values used for the generation of the utility function.

Table 4-7: Utility Values for the U-Value Criterion

U-Value Criterion								
Acceptability Range of U-Values $(W/m^2 . K)$		**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2.0**
Utility Values	(UQU) arch. A	1.00	0.80	0.70	0.60	0.45	0.20	0.10
	(Parsons) eng. S	1.00	0.90	0.85	0.70	0.50	0.30	0.15
	(RSA) arch. L	1.00	0.90	0.60	0.30	0.10	0.05	0.00
Average Utility Values		1.00	0.87	0.72	0.53	0.35	0.18	0.08

The utility function for the U-value criterion was developed based on the average utility values listed in Table 4-7. Figure 4-6 shows the utility function for the U-value criterion, which was generated by plotting at least two points: best and worst, as indicated in the figure. A window with a U-value of 1.4 is assigned the best utility score of 1.0 (best performance), while a window with a U-value of 2.0 is assigned a utility score of only 0.08 (worst performance). A window with any U-value between 1.4 and 2.0 is thus scored between 1.0 and 0.08.

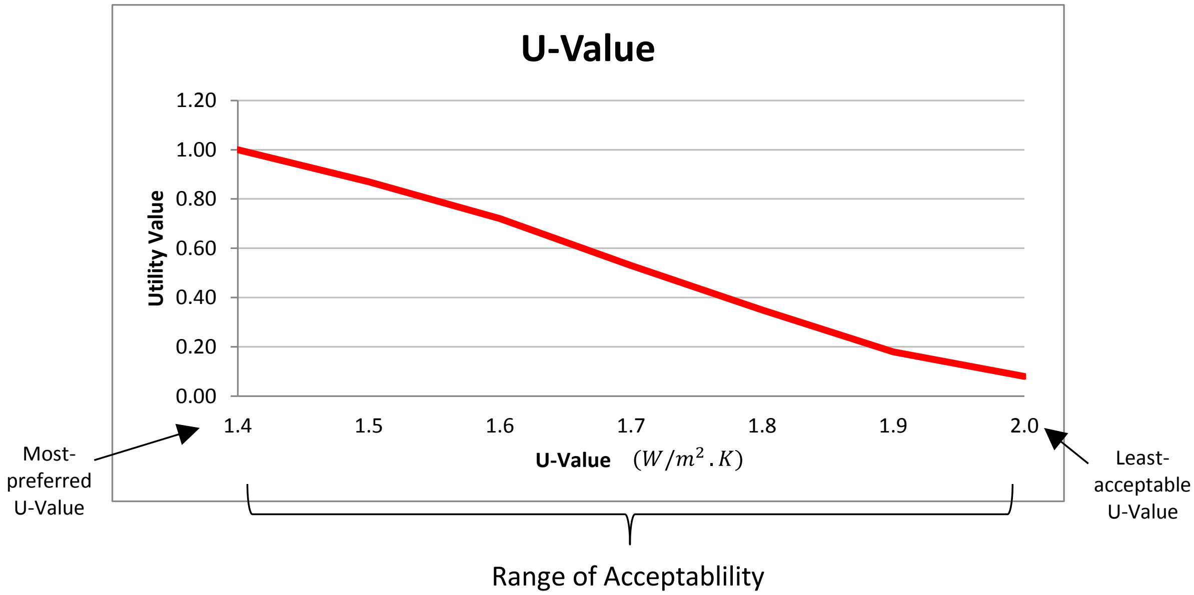


Figure 4-6: Utility Function for the U-Value Criterion

The utility value of any alternative within the acceptable range can be determined automatically and conveniently from the graph during the evaluation process. Multiplying the weight of the criterion (W_1) by the utility value (U_{i1}) produces the score for the U-value criterion (X_{i1}):

$$X_{i1} = W_1 * U_{i1} \tag{4-9}$$

The effective utilization of the scores during the submittal evaluation process is elaborated upon in Chapter 5, which explains the development of the framework.

4.2.2.2 Air Infiltration: Building Tightness

A significant amount of energy is consumed for heating buildings, with heat being transferred from buildings in two main ways: thermal conduction and air infiltration (convection). Air infiltration can have a significant impact on heat loss, energy use in buildings, thermal comfort, and indoor air quality. It is estimated that residential buildings use about 30 % to 50 % of the total energy they consume in order to condition the outside air that infiltrates the building (Colliver 2000).

Infiltration occurs when the inside-outside temperature ratio changes and/or the wind speed varies. The amount of infiltration is thus not constant but varies according to weather conditions such as wind speed, stack effects, and temperature differences. Air infiltration is therefore a wind-driven and temperature-driven phenomenon, defined by ASHRAE (2004a) as "the uncontrolled airflow through openings in a building envelope caused by the pressure effects of wind, the effect of differences in indoor and outdoor air density, or both (cubic feet per minute or cfm) [m^3/s]."

Air tightness (the quality of the building envelope related to air infiltration) is an important building property associated with infiltration because air infiltration occurs persistently through building components: gaps between steel frames, voids above ceilings, leaky HVAC systems, unsealed layers in built-up roof systems, permeable materials, and windows and doors. Heat lost or gained through air leakage contributes to the overall air infiltration into the building. A standard method of detecting and measuring air leakage and of pinpointing the specific locations of leaks for the entire building is therefore necessary (Varshney et al. 2013).

The quantification of the air tightness of buildings is typically called "air leakage" (Sherman 2009) and is usually measured by a process known as a blower-door or fan pressurization test, which was originally developed in Sweden in the 1970s (Kronvall 1978) and introduced to the U.S. through Princeton University (Blomsterberg and Harrje 1979). The American Society for Testing and Materials (ASTM) Standard E779 is now the official U.S. test method (ASTM 1999). The Canadian General Standards Board (CGSB) specifies a similar method (CGSB 149.10-M86) that has been commonly used in Canada since 1986 (CGSB 1986). Fan pressurization involves the use of a large door-mounted, variable-speed fan to create pressure differences between the interior of the building where all internal doors are open, and the exterior of the building with all external openings closed (windows, doors, etc.). The airflow rates through the fan (in cfm or m^3/h) that keep the pressure differences in the building at 50 pascals (a metric unit of pressure) are then measured and recorded. The air flow rate in cfm at a pressure differential of 50 pascals is commonly expressed as CFM50 (Ask 2003).

CFM50 is the result of blower door testing in an individual building, but it cannot be used to compare the tightness of different buildings unless it is "normalized" for the volume of each house. Therefore, CFM50 is multiplied by 60 (minutes/hour) and divided by the volume of the house in cubic feet (equal to one "air change") in order to yield a value called "air change per hour at 50 pascals," or ACH50 (Roberson 2004). The lower the ACH value, the tighter the building. It is important to note that an ACH value can be obtained only by testing an actual built building and that it cannot pinpoint the specific sources of leakage in the building tested (e.g., windows, ceilings, plumping, etc.).

The air leakage associated with windows, on the other hand, is measured through the physical testing of a fabricated standard-sized window (specimen) according to ASTM E-283 or the CSA-A440 series of window performance standards. On one side, a vacuum of 75 pascals is applied to the test window, which is installed in a large wall. This vacuum corresponds to an approximately 40 km/h (25mph) wind blowing perpendicularly to the window. Flow meters measure the rate of air leakage, which is divided by the total area of the window in order to obtain a reading in cubic metres per hour per linear metre of crack (m^3/h/m) or cubic feet per minute per linear foot of crack (cfm/ft). The air leakage rate can be reported in two ways: either averaged over the crack length or averaged over the frame area (RDH 2013). According to the CSA-A440-00 performance standard for windows (CSA 2006), the maximum air infiltration rate for a window must not exceed 2.79 (m^3/h)/m (approximately 0.5 cfm/ft). The best-functioning windows are rated A3 and have leakage rates of 0.55 (m^3/h)/m (approximately 0.1 cfm/ft). Table 4-8 shows the air leakage rates for windows based on the CSA-A440-00 performance standard for windows (CSA 2006).

Table 4-8: Air Leakage Rates for CSA Windows (CSA 2006)

Window Rating		Maiximum Air Leakage Rate CSA A440-00	
		$(m^3/h)/m$	$(cfm)/ft$
Storm	Worst Rating	8.35 (5.0 minimum)	1.5
A1		2.79	0.5
A2		1.65	0.3
A3		0.55	0.1
Fixed	Best Rating	0.25	0.04

Air infiltrates through multiple pathways in a window assembly; the most common are between the meeting rails and between the sashes and the frame (Baker 2012). Because these elements are operable, the passage of at least some air between them is unavoidable. Figure 4-7 illustrates the common pathways for air infiltration through windows.

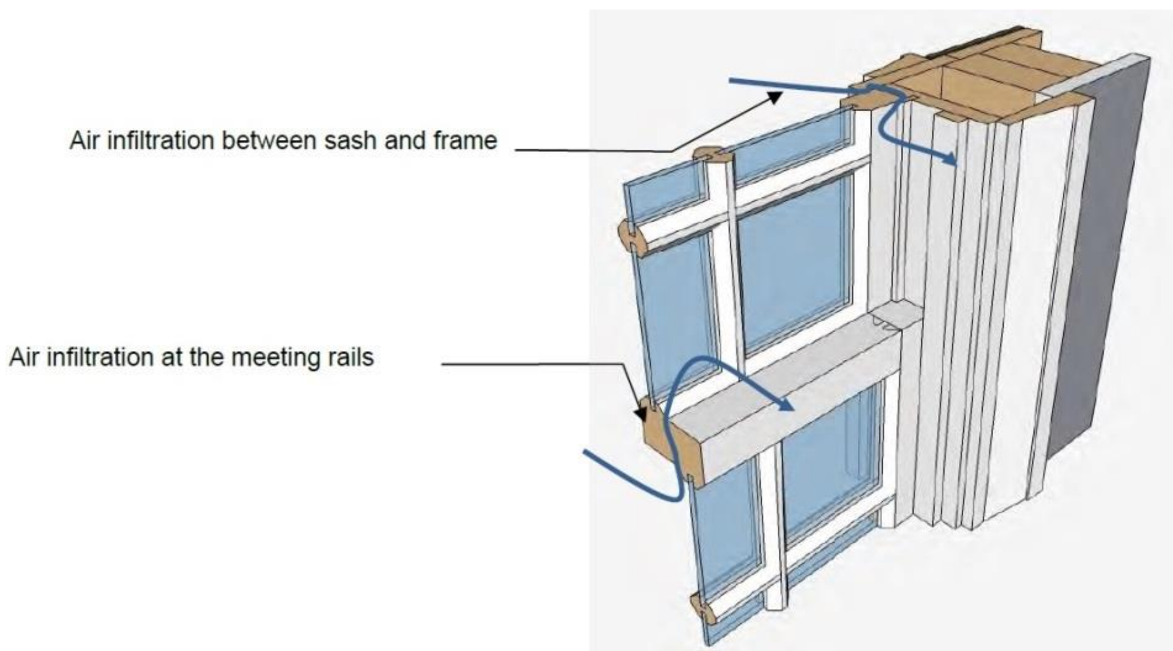


Figure 4-7: Air Infiltration Pathways of a Window (Baker 2012)

An understanding of how air infiltration affects building heating and cooling loads requires an explanation of the calculation of the amount of heat loss due to air infiltration. In general, heat loss caused by infiltration, Q_{inf}, is given by

$$Q_{inf} = C_p \times \rho \times ACH \times V \times (T_{in} - T_{out}) \tag{4-10}$$

where

Q_{inf} is heat loss from infiltration, in watts;

C_p is the specific heat of air [0.284 Wh/Kg.K];

ρ is the density of air [1.2 kg/m^3];

ACH is the rate at which the air changes per hour, in 1/h;

V is the volume of the building space, in m^3;

T_{in} is the inside temperature, in ^{o}C;

T_{out} is the outside temperature, in ^{o}C.

The assignment (*ACH* × *V*) in equation (4-10) represents the mass flow rate of the infiltration (cfm or m^3/h). To calculate the annual amount of energy required for heating or cooling as a result of infiltration, infiltration degree-days (IDDs) must be incorporated (Sherman 1986). A concept similar to degree-days, IDDs are a measure of climate severity as it affects infiltration loads (ASHRAE 2004a). The annual consumption of heating energy due to infiltration from all building components (not only windows) is given by the following:

$$Q_{heating.inf} = (C_p \times \rho \times ACH \times V \times HIDD)(24 \div 1000) \tag{4-11}$$

where

$Q_{heating.inf}$ is the energy consumption due to infiltration, in kWh;

HIDD is the number of heating infiltration degree-days, in °C-days.

The cost of the energy required for heating as a result of infiltration is given by

$$E_{heating.inf} = \left(Q_{heating.inf} \times P_g\right) \quad (4\text{-}12)$$

where

$E_{heating.inf}$ is the cost of the energy consumed for heating, in dollars;

P_{gas} is the monthly price of natural gas [0.022 $/kWh].

The amount of energy required for cooling as a result of infiltration is given by

$$Q_{cooling.inf} = (C_p \times \rho \times ACH \times V \times CIDD)(24 \div 1000) \quad (4\text{-}13)$$

where

$Q_{cooling.inf}$ is the energy consumption due to infiltration, in kWh;

CIDD is the number of cooling infiltration degree-days, in °C-days.

The cost of the energy required for cooling as a result of infiltration is given by

$$E_{cooling.inf} = \left(Q_{cooling.inf} \times P_e\right) \quad (4\text{-}14)$$

where

$E_{cooling.inf}$ is the cost of the energy consumed for cooling, in dollars;

P_e is the monthly price of electricity [0.09 $/kWh].

The total amount of energy consumed as a result of infiltration is given by

$$Q_{total.inf} = Q_{heating.inf} + Q_{cooling.inf} \tag{4-15}$$

The total cost of the energy consumed as a result of infiltration is given by

$$E_{total.inf} = E_{heating.inf} + E_{cooling.inf} \tag{4-16}$$

An assessment of the overall cost of the energy consumed as a result of infiltration requires an estimation of the air leakage rate (ACH50). According to the PassiveHaus standard, developed by an international organization originating in Germany, buildings must be designed to achieve no more than 0.6 ACH50. In Canada, residential houses, in general, have been improving with respect to air tightness, and new buildings located in Ottawa can achieve about 0.4 ACH50 (CMHC 2008).

To analyse the effect of infiltration associated with windows on the total energy cost of the building, the sample building from Figure 4-4 was examined and assigned an assumed rating of 0.6 ACH50. The volume of the building is 26,400 m^3 (based on a floor area of 800 m^2 and a height of 33 m), and the HIDDs and CIDDs are assumed to be 3714 and 868, respectively (Sherman 1986). In a typical Canadian house, the air leakage through windows can reach up to 12 % of the total leakage from all sources (Union Gas 2010). Assuming that the 12 % window leakage scenario occurs through windows with the best airtightness rating (A3), as shown in Table 4-9, the 12 % increases proportionally when windows that are less tight are used. For example, the window air leakage can be assumed to increase to 15 % and 18 % for A2 and A1 windows, respectively. To illustrate the change in consumption that occurs with changes in the air tightness ratings, windows with three levels of air tightness ratings were assessed. Table 4-9 indicates the effect of using the best-rated windows (A3) in the 0.6 ACH50 sample building compared to the effect of using windows with other ratings.

Table 4-9: Effects of Using Windows with Different Airtightness Ratings

Volume of Building: 26,400 m^3						
Air Leakage Rate: 0.6 ACH50						
$E_{total.inf}$ *	Window Rating		Percentage of Infiltration through Windows		Annual Cost of Energy due to Window Infiltration	
$20,707	**A3** 0.55 $(m^3/h)/m$	Best Rating	12%		$2,485	
	A2 1.65 $(m^3/h)/m$		15%	$1,242	$3,106	$621
	A1 2.79 $(m^3/h)/m$	Worst Rating	18%		$3,727	

* Based on eq. (4-16)

The annual total energy consumption of the sample building costs about $20,707, as shown in Table 4-9. This amount represents the energy cost arising from air leakage from all sources throughout the building, including windows. The use of the best-rated windows is associated with annual costs of about $2,485, which rises to $3,106 when the windows are changed to those with the next-best rating (A2). Although the change produces about three times as much air infiltration (from 0.55 $(m^3/h)/m$) to 1.65 $(m^3/h)/m$), the extra cost implication of $621 is negligible. However, the additional cost reaches $1,242 for the poorest air infiltration window rating of 2.79 $(m^3/h)/m$), which is barely acceptable in a tight building design. Therefore, the extra cost resulting from a change to windows with a different air tightness rating during the submittal evaluation process has not been taken into consideration in the framework assessment portion of this research.

This example demonstrates that evaluating the air infiltration rating of windows is critical because their air tightness is linked to the calculations related to the energy consumption component of building performance. Because the increase in operational costs associated with a change to the worst-rated windows (A1) is negligible compared to the considerable operational cost imposed by deviating to window units with the least acceptable U-value (Figure 4-5), it was determined that no compensation would be associated with this criterion during the development of the evaluation framework. The operational compensation is therefore limited to the energy lost through conduction.

The air infiltration criterion plays a major role in evaluating window submittals. Despite the fact that windows are associated with a relatively negligible energy cost, windows with the top tightness rating are always required, and this standard should not be compromised. To ensure the appropriate window selection, an acceptable range of air tightness ratings must be defined, followed by the generation of the utility function that quantifies the practitioners' preference. Table 4-10 shows the acceptable range for the air infiltration rate criterion, the utility values suggested by each practitioner, and the average values used for the generation of the utility function.

Table 4-10: Utility Values for the Air Infiltration Criterion

Air Infiltration Criterion					
		Fixed	A3	A2	A1
Acceptable Range of Air infiltration Rates $(m^3/h)/m$		**0.25**	**0.55**	**1.65**	**2.79**
Utility Values	(UQU) arch. A	1.00	1.00	0.70	0.30
	(Parsons) eng. S	1.00	1.00	0.80	0.20
	(RSA) arch. L	1.00	1.00	0.50	0.10
Average Utility Values		1.00	1.00	0.67	0.20

The utility function for the air infiltration rate criterion was developed based on the average utility values listed in Table 4-10. Figure 4-8 shows the utility function for the air infiltration rate criterion and indicates the least- and most-preferred values.

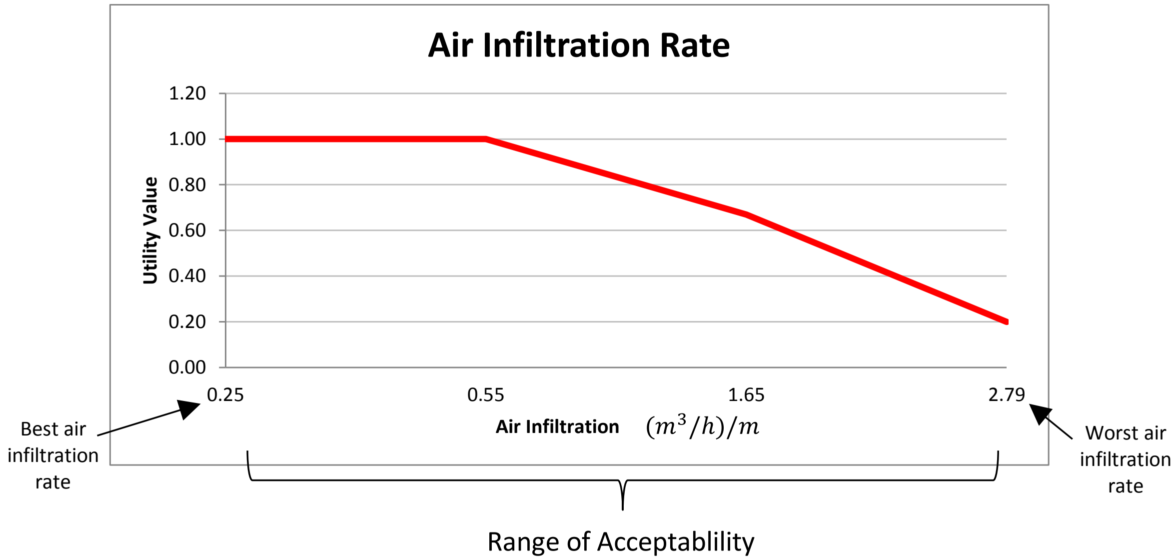


Figure 4-8: Utility Function for the Air Infiltration Criterion

The score for the air infiltration criterion (X_{i2}) is derived from the utility value (U_{i2}) of the selection multiplied by the weight of the criterion (W_2), as follows:

$$X_{i2} = W_2 * U_{i2} \tag{4-17}$$

4.2.2.3 Water Penetration

For the past four decades, the poor performance of building enclosures in Canada and elsewhere has repeatedly been linked to inferior window quality (CMHC 2003). In 1964, the *Canadian Building Digest* stated, "Rain penetration is a major problem with glazing and must be controlled…" (Garden 1964). Since that time, water penetration problems associated with windows have been a major challenge that has a severe effect on both building performance and indoor air quality.

Water penetration occurs through a building enclosure when three factors are consistently applied: the presence of water, the presence of exterior openings and unintentional gaps or joints, and the physical forces that naturally move water (Beall 1999). Water can interact with a building enclosure as rain, melting snow, or moisture. Openings are added to buildings for entry and egress and to permit the admittance of daylight, ventilation, and utilities. Such openings create unintentional gaps, voids, cracks, and joints that allow uncontrolled water penetration through several natural forces, including gravity, capillary suction, surface tension, kinetic energy (momentum), and pressure differences (Lstiburek and Carmody 1993). When rain blows into a window assembly, gravity causes the water to drain downward into the walls through the window sill, which is the most vulnerable and leak-prone element of a window (Olson et al. 2009). The momentum of blowing rain on windows can create numerous pathways that have the potential for water penetration. Figure 4-9 illustrates the common pathways, which can be categorized as follows (Baker 2012):

- Between the window frame and the rough opening;
- Through the joints in the window frame;
- Between the window frame and the operable sashes;
- Through the joints between the glass and the sash frames.

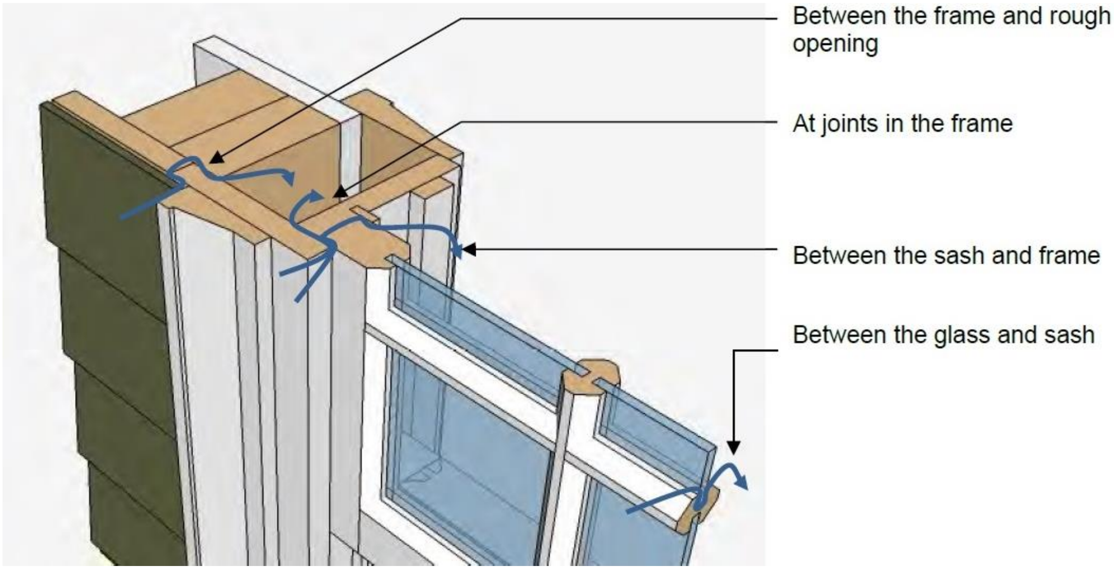


Figure 4-9: Common Water Penetration Pathways (Baker 2012)

The persistent penetration of water into a building enclosure increases the level of moisture, which leads to the proliferation of fungus; stained carpets and drywall; and ultimately, an uncomfortable and unhealthy indoor environment. To limit or minimize water penetration, windows should be tested with respect to specific physical and performance criteria. The CSA-A440 series of windows performance standards were developed in part to provide a basis for the evaluation and categorization of the level of rain penetration control. CSA-A440-00 specifies laboratory testing of water penetration resistance in accordance with ASTM E 547, *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference*. The water penetration ratings for CSA windows are listed in Table 4-11.

Table 4-11: Water Penetration Ratings for CSA Windows (CSA 2006)

Window Rating			Pressure Differential (Pa)
For Use in Small Buildings	For Use in Other Buildings		
Storm	_		0
B1	B1	Worst Rating	150
B2	B2		200
B3	B3		300
_	B4		400
_	B5		500
_	B6		600
_	B7	Best Rating	700

Table 4-11 shows seven water tightness ratings for windows, with B1 as the poorest rating and B7 as the best rating. B7 indicates that during the 24-minute test period, with a pressure differential of 700 Pa (14.6 psf), no water leakage was observed, and the window system thus met the CSA-A440-00 performance requirements for a B7 Water Tightness rating.

While the severity of the impact of water penetration on a building is clear, no specific method exists to enable the calculation or assessment of the effect of the window penetration rate on building performance at the design stage of a project. The testing and assessment can be conducted only on site for installed windows based on the field analogue to the ASTM E 547 laboratory test referenced by CSA-A440: ASTM E 1105, *Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Air Pressure Difference*. However, most specifications do not require field tests of the installed items (RDH 2002; Olson et al. 2009). As a result, window installation can result in additional negative effects, such as replacement or exhaustive renovation work, especially if an item is submitted with a minor deviation. Ensuring the optimal selection of windows at the submittal evaluation stage prior to construction is therefore imperative.

Achieving this goal requires the definition of an acceptable range of air tightness ratings, followed by the generation of the utility function that quantifies the practitioners' preferences. Table 4-12 shows the acceptable range for the air infiltration rate criterion, the utility values suggested by each practitioner, and the average values used for the generation of the utility function.

Table 4-12: Utility Values for the Water Penetration Criterion

Water Penetration Criterion								
		B7	B6	B5	B4	B3	B2	B1
Acceptable Range of Water Penetration Rate (Pa)		**700**	**600**	**500**	**400**	**300**	**200**	**150**
Utility Values	(UQU) arch. A	1.00	0.95	0.80	0.60	0.40	0.20	0.00
	(Parsons) eng. S	1.00	0.90	0.70	0.50	0.30	0.20	0.00
	(RSA) arch. L	1.00	0.90	0.60	0.30	0.20	0.10	0.00
Average Utility Values		1.00	0.92	0.70	0.47	0.30	0.17	0.00

The utility function for the water penetration rate criterion was developed based on the average utility values listed in Table 4-12. Figure 4-10 shows the utility function for the water penetration criterion and indicates the least- and most-preferred values.

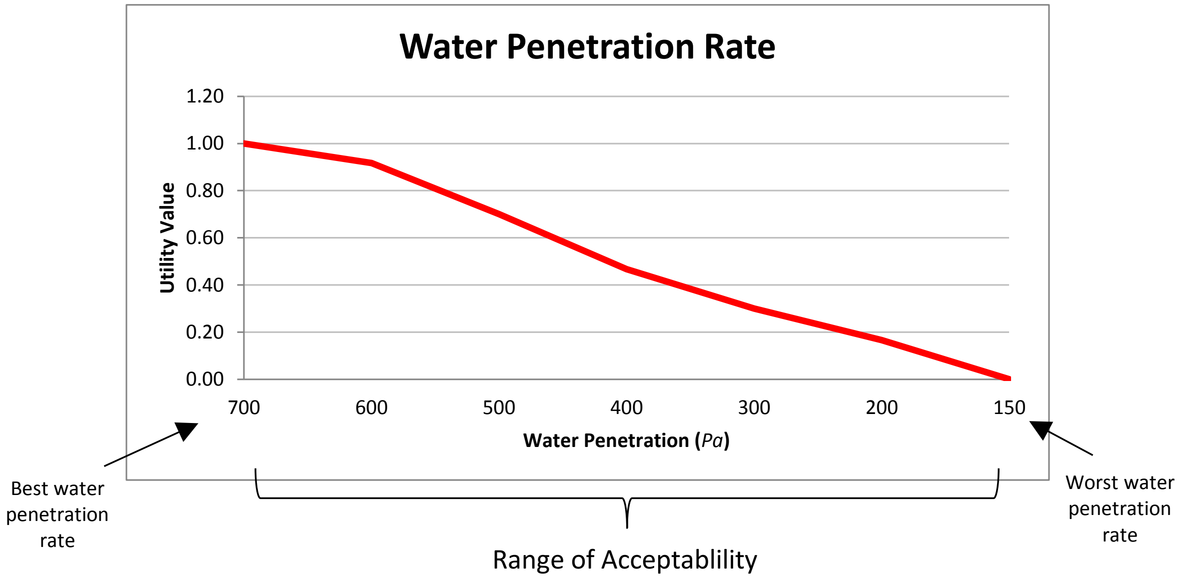


Figure 4-10: Utility Function for the Water Penetration Criterion

No additional cost is associated with the water penetration criterion. The score for the water penetration criterion (X_{i3}) is derived from the utility value (U_{i3}) of the selection multiplied by the weight of the criterion (W_3), as follows:

$$X_{i3} = W_3 * U_{i3} \tag{4-18}$$

4.2.2.4 Visible Transmittance

Visible transmittance (VT) refers to the fraction of light in the visible portion of the spectrum that passes through a glazing material (Carmody 2004). The size of the fraction is influenced by the type of glazing selected, the number of panes, and the glass coatings as well as by non-transparent components such as the frame and sash. The VT ratings listed on CSA and NFRC window labels include the frame and sash, not just the glass, which is important because VT values for the entire window are always less than the centre-of-glass values since the VT of the frame is zero. A higher VT indicates the possibility of more daylight in a space (e.g., for a window with a VT of 0.80, 80 % of visible daylight is allowed through the window), and coupled with effective design, can offset artificial lighting and its associated cooling loads. A reduction in the VT is normally correlated with a reduced SHGC.

In general, all low-E coatings reduce visible light transmittance to some extent, and some coatings may appear slightly tinted or more reflective under specific lighting conditions. The VT values of glazing range from above 0.90 for uncoated water-white clear glass to less than 0.10 for highly reflective coating on tinted glass. For example, clear double-glazing has a VT of approximately 80 %. With hard-coat low-E glazing, that figure drops to 75 %, and with new spectrally selective coatings, it falls further to approximately 70 %. Most tinting is not noticeable until the VT of the glazing falls below approximately 60 %. Table 4-13 shows the acceptability range for the VT criterion, alternatives, the utility values suggested by each practitioner, and the average values used for the generation of the utility function.

Table 4-13: Utility Values for the Visible Transmittance (VT) Criterion

Visible Transmittance (VT) Criterion						
Acceptable Range of Visible Transmittance		50%	60%	70%	80%	90%
		0.50	**0.60**	**0.70**	**0.80**	**0.90**
Utility Values	(UQU) arch. A	0.40	0.70	0.80	0.90	1.00
	(Parsons) eng. S	0.30	0.50	0.70	0.80	1.00
	(RSA) arch. L	0.50	0.60	0.70	0.80	1.00
Average Utility Values		0.40	0.60	0.73	0.83	1.00

The utility function for the VT criterion was developed based on the average utility values listed in Table 4-13. Figure 4-11 shows the utility function for the VT criterion and indicates the least- and most-preferred values.

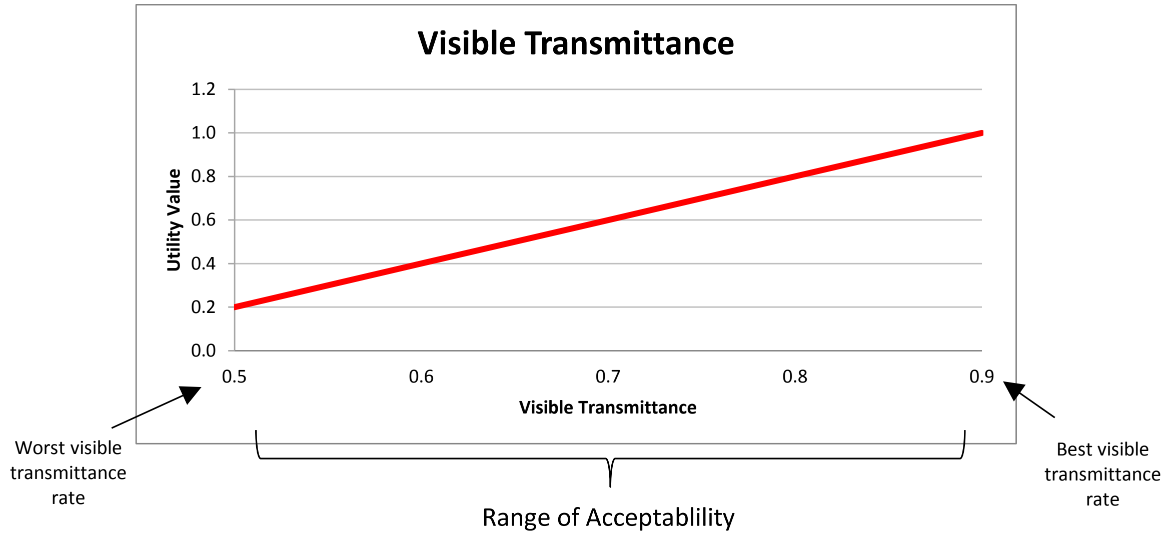


Figure 4-11: Utility Function for the Visible Transmittance Criterion

No additional cost is associated with the VT criterion. The score for the VT criterion (X_{i4}) is derived from the utility value (U_{i4}) of the selection multiplied by the weight of the criterion (W_4), as follows:

$$X_{i4} = W_4 * U_{i4} \tag{4-19}$$

4.2.2.5 Solar Heat Gain Coefficient

Controlling solar heat gain through glazing is a major energy-performance aspect of windows. Direct and diffuse radiation emitted from the sun and the sky represents the primary source of a building's solar heat gain. Specifically, when sunlight hits a window, some solar radiation is transmitted through the glazing to the building's interior, some sunlight is reflected back to the exterior, and some is absorbed in the glazing and indirectly admitted to the building's interior. The opaque and conductive material of the window frame absorbs some heat, which can be emitted to either the interior or exterior of the building. The solar heat gain coefficient (SHGC) represents the fractional amount of solar heat (energy) that is admitted through a window, both by direct transmission and by absorption; that is subsequently released inward; and that finally becomes a factor in warming the building's interior (Carmody 2004; ASHRAE 2009). Figure 4-12 shows the components of solar heat gain, including transmitted solar energy and reflected and absorbed radiation.

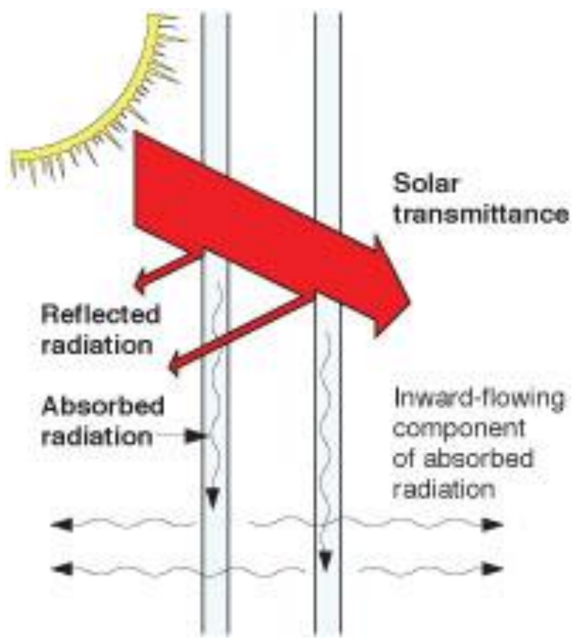


Figure 4-12: Components of Solar Heat Gain (Carmody 2004)

The SHGC has replaced the previous standard indicator of the shading ability of a window: the shading coefficient (SC). SHGC values are generally lower than SC levels. The SHGC is expressed as a dimensionless number from 0 to 1. For example, for a window with an SHGC of 0.49, 49 % of solar heat is transmitted through the window assembly. The lower the SHGC, the less solar heat is transmitted. In other words, a high SHGC signifies substantial solar heat gain. For buildings in cold climates, windows with a high SHGC are thus required in order to increase passive solar gain. Solar heat gain is influenced by glazing type, number of panes, and glass coatings. The solar heat gain of glazing ranges from over 80 % for uncoated water-white clear glass to less than 20 % for highly reflective coatings on tinted glass. A typical double-pane insulated glass unit (IGU) has an SHGC of approximately 0.70. This value is decreased somewhat by the addition of a low-E coating, and tinting reduces it substantially. Since the frame has a very low SHGC, the SHGC of the overall window is lower than the centre-of-glass value. Because the SHGC is affected by the glazing-to-frame ratio, the SHGC for the whole window unit has been adopted in this research.

Table 4-14 shows the acceptability range for the SHGC criterion, alternatives, the utility values suggested by each practitioner, and the average values used for the generation of the utility function.

Table 4-14: Utility Values for the Solar Heat Gain Coefficient (SHGC) Criterion

Solar Heat Gain Coefficient (SHGC) Criterion							
Acceptable Range of the Solar Heat Gain Coefficient (SHGC)		**0.00**	**0.20**	**0.40**	**0.60**	**0.80**	**1.00**
Utility Values	(UQU) arch. A	1.00	1.00	1.00	0.95	0.70	0.30
	(Parsons) eng. S	1.00	1.00	1.00	0.90	0.75	0.60
	(RSA) arch. L	1.00	1.00	1.00	0.80	0.70	0.50
Average Utility Values		1.00	1.00	1.00	0.88	0.72	0.47

The utility function for the SHGC criterion was developed based on the average utility values listed in Table 4-14. Figure 4-13 shows the utility function for the SHGC criterion and indicates the worst and best SHGC values.

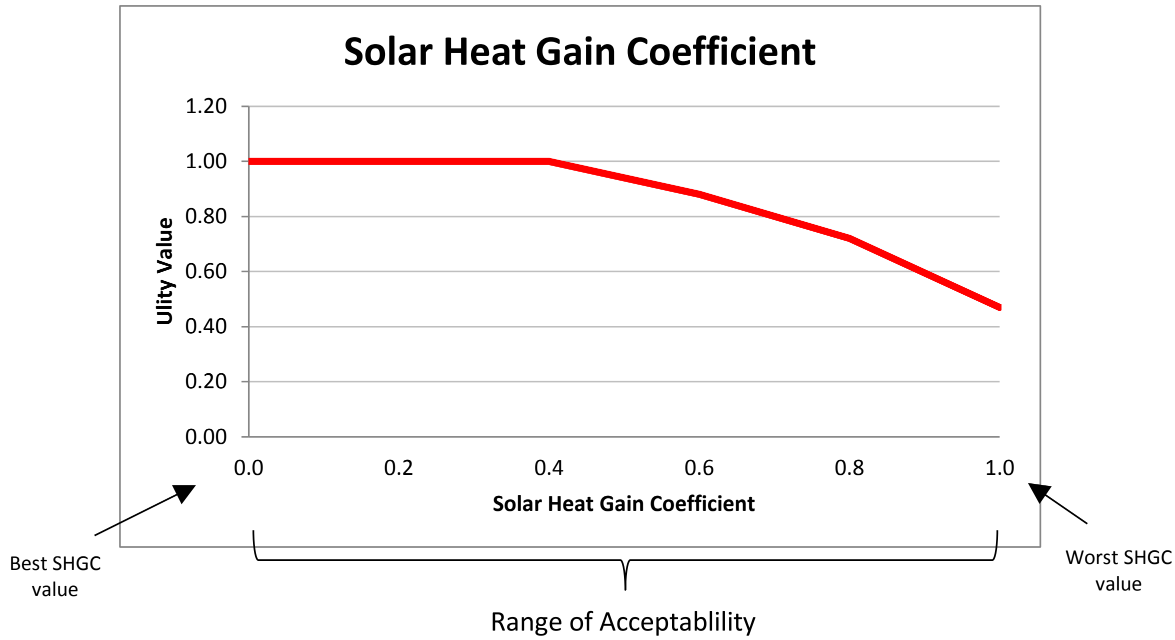


Figure 4-13: Utility Function for the Solar Heat Gain Coefficient (SHGC) Criterion

No additional cost is associated with the SHGC criterion. The score (X_{i5}) is given by

$$X_{i5} = W_5 * U_{i5} \tag{4-20}$$

4.3 Conclusion

This chapter has detailed the investigation of the evaluation criteria for windows. Based on practitioner feedback, the listed criteria have been categorized as one of two types: design rationale or performance-related. Design rationale criteria include all criteria that are described in textual and qualitative formats, whereas performance-related criteria comprise all criteria represented numerically and quantitatively. Analytical hierarchy process (AHP) weights have been assigned, and utility functions have been generated based on feedback contributed from a number of organizations. Performance-related criteria have been introduced and explained as technical factors that affect overall building performance. As shown in Table 4-15, based on government requirements, standards, and practitioners' preferences, default requirements for these performance-related criteria have been finalized for further application as a basis of comparison. Methods of calculating the energy associated with the U-value and air infiltration criteria have been explained using an illustrative example. All of the evaluation criteria that were incorporated into the development of the evaluation framework have been examined, as presented in the next chapter.

Table 4-15: Default Requirements for Performance-Related Criteria

Performance-Related Criteria	Requirements	References
U-Value	1.4 $(W/m^2 . K)$	ENERGY STAR Program (NRCAN 2011b)
Air Infiltration	0.55 $(m^3/h)/m$	CSA-A440-00 (CSA 2006)
Water Penetration	700	CSA-A440-00 (CSA 2006)
Visible Transmittance (VT)	0.9	Practitioners Feedback
Solar Heat Gain Coefficient (SHGC)	0.3	Practitioners Feedback

Chapter 5

BIM-Based Submittal Evaluation Framework

5.1 Introduction

This chapter introduces the conceptual approach for the development of a BIM-based decision support framework designed to provide efficient assistance for project managers who are evaluating key architectural submittals during construction. The drawbacks of traditional procedure have been addressed through the incorporation of an automated, integrated BIM platform and decision support tool, which are described in detail. To enable an understanding of the workflow of the evaluation process, the phases, mechanisms, and all related steps in the proposed framework are explained in depth. With the framework as a basis, a prototype system was created and implemented for a hypothetical case study in order to evaluate the effectiveness of the system. The particulars and results of the case study are presented.

5.2 Conceptual Approach

The goal of the submittal evaluation process, which is required for all types of contracts, is to enable the examination of all products and materials prior to fabrication or installation as a means of ensuring consistency with the drawings and specifications. As discussed in Chapter 2 and confirmed by practitioners during the data collection and analysis stages of this research, the traditional procedure for evaluating submittals involves drawbacks and challenges that can result in inefficient or detrimental decisions. The very nature of the procedure opens the door for subjective decisions based on experience, background, or intuition. Such decisions can affect the time, budget, schedule, and productivity of a project, and most importantly, can also have a negative impact on long-term building performance. The drawbacks of the traditional procedure are summarized in Table 5-1.

Table 5-1: Drawbacks of Traditional Submittal Evaluation

	Summary of Submittal Drawbacks
1	Drawings, specifications, submittal transmittals, and evaluation criteria are all scattered among different file formats.
2	Available submittal systems can not accomodate customization or development.
3	Evaluation outcomes can be inappropriate because of subjective and experience-based decision.
4	Rigorous evaluation is not possible due to the rough specifications and time constraints.
5	The contractor cannot perform a self assessment before delivering the offical submittals.
6	No structured/automated evaluation mechanism is available.
7	Submittals with minor changes or deviations are automatically rejected although they may add significant value to a project.
8	Construction and operational implications are not considered.
9	Approved submittals are not effectively documented/updated in a system.

All submittals must comply with predefined design rationale criteria and also satisfy performance-related criteria as determined through a detailed analysis and structured mechanism. In actual practice, however, unforeseen market conditions, incomplete designs, or roughly described items may result in submittals that are only partially compliant. To save project time and add value to project, it is beneficial to conditionally accept submittals with trivial deviations from the specifications for further consideration, especially if they provide additional value and cost savings to the project in short and long terms. Conditional acceptance, in this context, means that compensation must be provided by the contractor for any additional costs associated with the acceptance of the items involved. Even a conditionally accepted item that appears to be adequate during the construction phase may produce undesirable effects during operation and eventually create additional costs over the life cycle of the building. For conditionally accepted submittals, therefore, the construction-related impact (e.g., extra handling/installation charges) needs to be covered/absorbed, and operation-related consequences, (e.g., extra energy consumption) must be carefully estimated and taken into consideration as a basis for compensation (e.g., price reduction) and as a condition of acceptance.

The development of a submittal evaluation framework that overcomes the drawbacks of traditional procedures and that adheres to the conceptual approach involved two primary aspects. The first was the utilization of a customizable 3D-BIM platform as a depository for storing the specification data, drawings, and evaluation criteria. The second aspect was to employ an evaluation mechanism that utilizes a structured decision support tool to facilitate the rigorous evaluation of the submittals and that also incorporates consideration of any impact on construction and operational costs. The automated integration of these aspects results first in a thorough analysis of the available options and then in the determination of the decision that best ensures the successful delivery of the project. Figure 5-1 illustrates the concept on which the framework is based.

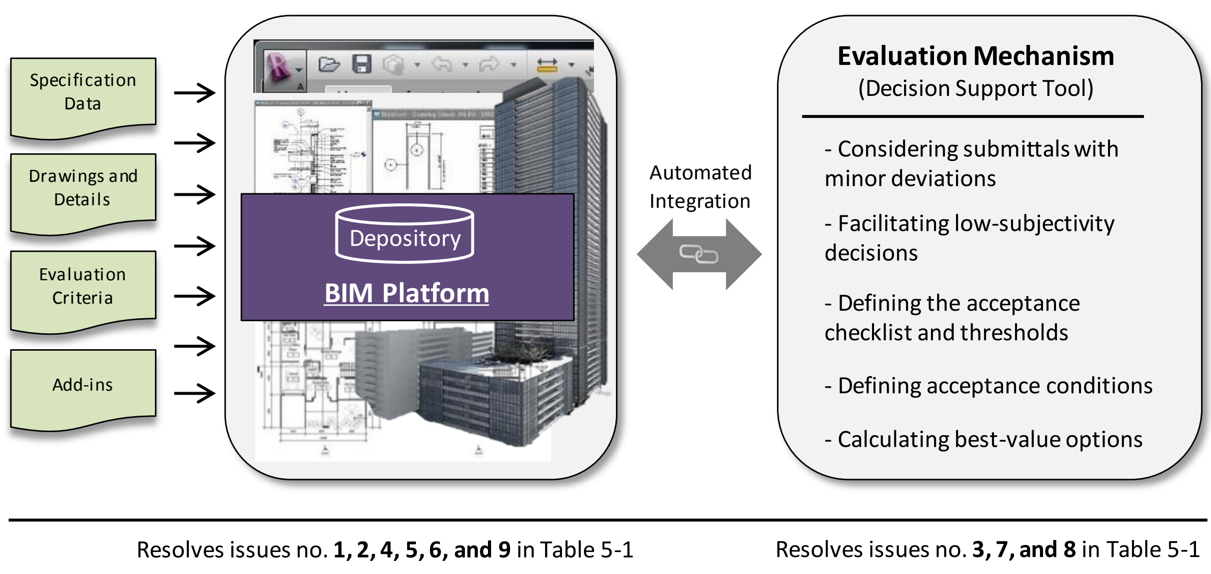


Figure 5-1: Conceptual Basis of the Framework

The conceptual framework offers the potential to resolve the drawbacks associated with traditional evaluation procedures. For example, the problem of scattered data can be resolved if a depository is used to contain all required information. An automated link between the BIM platform and the decision support tool provides a speedy method of producing less subjective decisions. Through a series of systematic steps, submittals that involve only minor deviations can be evaluated with respect to defined acceptance thresholds and conditions in order to arrive at the best-value option. The automation of the framework also enables construction and operational implications to be included in the evaluation. The development process and the creation of the working mechanisms involved in the framework are explained in the following section.

5.3 BIM-Based Submittal Evaluation Framework

The goal of this research was to develop a BIM-based decision support framework that can help project managers evaluate key architectural submittals during construction in an efficient and speedy manner. The conceptual work flow shown in Figure 5-1 was adopted for the creation of a structured/automated mechanism (framework) that would incorporate diverse tools and components in order to achieve an integrated framework. The evaluation process required a sequence of phases that would result in the identification of the best-value submittals for final approval. As a means of accommodating the varied requirements of different organizations/owners, the framework is comprised of two main phases: the framework setup and the submittal evaluation process (as shown in Figure 5-2). Each phase involves several accumulated/compiled steps (five in total for both phases combined) that create the working mechanism of the framework. For convenience and flexibility, step 1 is facilitated in a decision support tool, while all other steps are performed using a BIM platform. The phases, working mechanism, and all related steps in the framework are depicted in Figure 5-2.

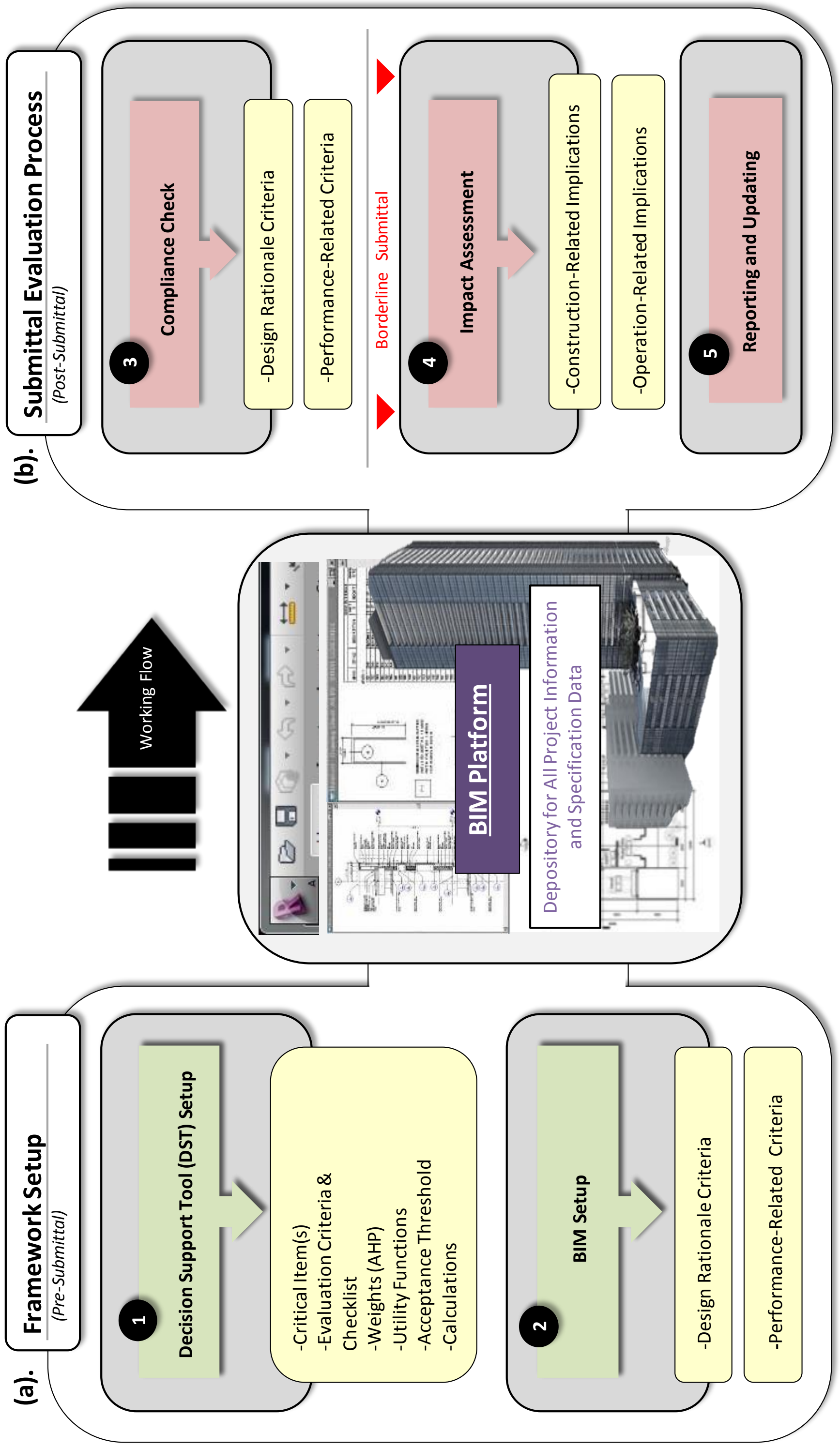


Figure 5-2: Framework Phases and Working Mechanism

5.3.1 Framework Setup

The setup phase is intended as an opportunity to expand the information available in the framework through the addition of specific organizational/owner preferences and requirements. This phase, which is performed before construction begins, consists of two steps: Decision Support Tool (DST) Setup and BIM Setup.

5.3.1.1 Decision Support Tool Setup

At the DST Setup level, the framework is fed with data that reflect the preferences, constraints, and requirements as provided by the decision makers, with the goal of achieving specific objectives: the identification of evaluation criteria for the top critical item, the assignment of weights, the generation of utility functions, the setting of an acceptance threshold, and the establishment of methods for calculating the implications. Prior to the start of construction, the objectives are defined and can be modified by the project team for each new project based on project constraints, adopted standards or building codes, the project location/zone, and required performance levels. In this step, a pair-wise comparison approach based on the analytical hierarchy process (AHP) developed by Saaty (1980; 1990) was adopted for the assignment of weights, and multi-attribute utility theory (MAUT) was utilized for the generation of utility functions for all performance-related criteria. Both the utility functions and the weights were then applied for the determination of overall scores (utilities) that must satisfy the minimum acceptance threshold for any submittal. The acceptance threshold is set by the project team based on previous projects and on the identification of high-priority issues specific to the current project. Calculation methods used for the assessment are based on heat loss and energy consumption calculations. This step can be considered the backbone of the framework because all of the additional steps are dependent on the retrieval and extraction of information from the decision support tool.

5.3.1.2 BIM Setup

BIM Setup, which is the second step in the Framework Setup phase, includes the customization of the BIM platform to enable the storage, editing, and management of specification data for the building components. Customization also enables designers to add all design rationale and performance-related criteria for critical architectural items into the BIM 3D-model. This step includes the addition of a customized add-in button to the BIM platform in order to facilitate the subsequent evaluation process. The customization also involves the editing of the “Properties” of the item to include additional fields that enable the evaluation criteria to be stored and recorded. Figure 5-3 shows the customized add-in button incorporated into the BIM platform as well as the customized data storage.

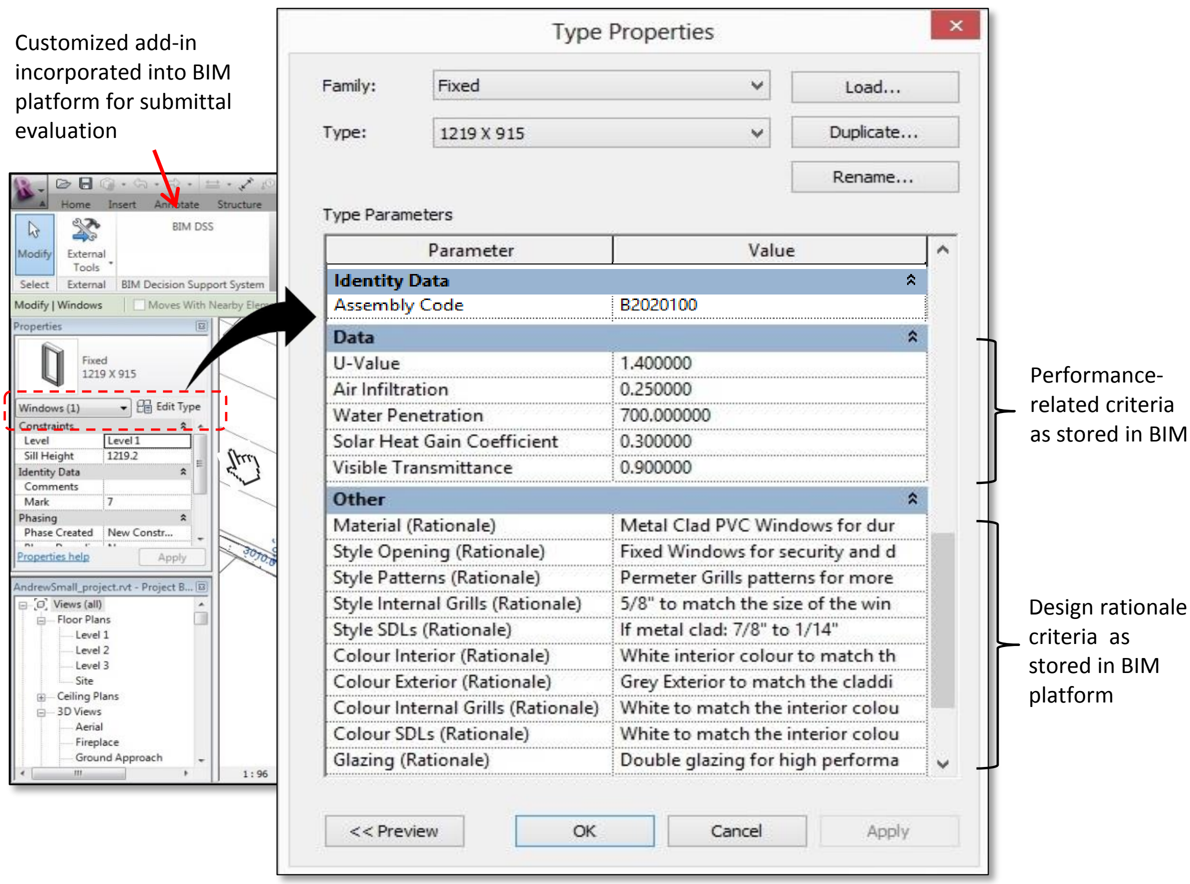


Figure 5-3: BIM Setup with Design Rationale and Performance-Related Criteria

As shown in Figure 5-3, the evaluation criteria are recorded as customized attributes associated with the parametric properties of 3D items in the BIM platform. The "Type Properties" dialogue box for the item has been designed so that it conveniently accepts all formats of evaluation criteria, whether textual or numerical.

In the framework, the design rationale is represented by a set of rationale criteria, each of which has a range of acceptability or tolerance (e.g., acceptable frame material, ranges of colour, types of glazing, etc.) set by the designers based on the preliminary design concept, owner preferences, the type and location of the project, the esthetic impact, etc. For example, for the frame material criterion, designers are required to identify the material used for a specific window, the rationale behind the selection, and another acceptable material that closely complies with the design rationale. In this context, for example, a frame material can be stored as aluminum-clad wood (*material*) to provide a luxurious indoor and neat-edge outdoor impression and to ensure durability and minimum thermal conductivity (*design rationale*), with acceptable alternative options of complete wood or PVC-clad wood (*range of acceptability*). This simple method of augmenting the BIM model ensures that a selected item fulfills the architectural requirements of the design. This approach has a beneficial effect on a project because of the enhancement of communication and productivity that result when all project parties are kept equally informed.

Performance-related criteria, on the other hand, are extracted from the technical specifications and then documented/stored in numerical format in pre-assigned BIM fields. In this study, performance-related criteria are assumed to be based on energy ratings (NRCAN 2011b) and A440 performance standards for windows (CSA 2006). To avoid problems arising from rough specifications or missing information, the BIM Setup step is intended to be completed during the building design process so that all evaluation criteria are available at the time scheduled for submittal evaluations.

5.3.2 Submittal Evaluation Process

The submittal evaluation phase is performed during construction and, through a designed and structured mechanism, is intended to help project managers select the best option for the project based on consideration of the architectural and technical aspects of each option. The workflow of this phase is designed to function as a loop, starting with the extraction of the submittal item from the 3D-BIM model, followed by the checking, assessing, and reporting steps, and ending with the updating of the 3D-BIM model with the approved option. The submittal evaluation process consists of three steps: “Compliance Check,” “Impact Assessment,” and “Reporting and Updating,” as shown in Figure 5-2b.

5.3.2.1 Compliance Check

Buildings are designed based on specific standards for the performance of individual functions. Each element in the building enclosure is intended to contribute a particular function; therefore, any change or modification to that element can directly or indirectly affect the performance of the entire building. Compliance analysis requires observance of both the design rationale and the performance-related criteria associated with the submittal under evaluation (item 3 in Figure 5-2). The two separate types of criteria are checked in different ways. Design rationale criteria lend themselves to a checklist type of evaluation, while performance-related criteria can be checked against specific acceptance thresholds.

Checking compliance with the design rationale requires careful attention to the predefined checklist. Since most of the checklist items are not derived from legal documents such as drawings and specifications, significant opportunity exists for them to be neglected or missed during the submittal evaluation. Therefore, in the compliance check step, submitted items must comply fully with the predefined list of design rationale criteria, with no possibility of or tolerance for compromise. Any item that exhibits only partial compliance is rejected, and the submittal is considered denied.

Items that comply with the design rationale checklist are then evaluated with respect to technical factors: performance-related criteria. When interrelated parameters are involved, the evaluation of such criteria requires a structured mechanism so that subjective decisions are minimized. AHP and MAUT have been adapted in order to facilitate the functioning of the mechanism for this step, so that the compliance of a submittal with performance-related criteria can be assessed objectively. Balancing the performance required of an item and slight changes in the item submitted constitutes the essence of this step of the evaluation. The goal is to enhance the smooth progress of the project without compromising the requirements expressed in the specification data. To facilitate this step, the overall score (utility) for each submittal option is calculated by multiplying the weights and utility values (determined from the utility curves) and then summing all of the scores to obtain performance levels for all options. For a submittal to be considered conditionally accepted, which is referred to as a borderline submittal in this study, these levels must satisfy a predefined acceptance threshold. The threshold is determined based project constraints, requirements, priorities, and practitioners' recommendations. Table 5-2 provides a summary of the process for calculating a submittal option score that indicates its compliance with performance-related criteria.

Table 5-2: Summary of the Calculation of the Score

Performance-Related Criteria	Weights	Utility Values	Scores (X_i)
U-Value	W_1	U_{i1}	$X_{i1} = W_1 * U_{i1}$
Air Infiltration	W_2	U_{i2}	$X_{i2} = W_2 * U_{i2}$
Water Penetration	W_3	U_{i3}	$X_{i3} = W_3 * U_{i3}$
Visible Transmittance (VT)	W_4	U_{i4}	$X_{i4} = W_4 * U_{i4}$
Solar Heat Gain Coefficient (SHGC)	W_5	U_{i5}	$X_{i5} = W_5 * U_{i5}$
Total Score $(X_i) = X_{i1} + X_{i2} + X_{i3} + X_{i4} + X_{i5} >= Acceptance\ Threshold$			

5.3.2.2 Impact Assessment

In practice, receiving items with minor changes from the required specifications is frequently occurring. Any changes that occur during construction can result in different degrees of consequences for the required performance of the building with respect to resources, productivity, energy consumption, or operation. While the discrepancy might be within an acceptable range, any additional cost implications should also be taken into consideration.

Acceptable borderline submittal options resulting from the "Compliance Check" step are assessed with respect to their impact on construction and operational factors. Construction-related implications are related to the quantification of all construction costs and delays arising from the acceptance of the borderline submittals. Any construction issue, such as changes in price or additional installation fees, storage/handling fees, or delivery time must be disclosed by the contractor as part of this step; otherwise, a borderline option is not considered during the decision-making process. The construction implications are the responsibility of the contractor and must be reported by him/her if borderline items are to be approved.

Operation-related implications refer to the forecasting of all additional operation-related costs along the entire life cycle of the building. Energy consumption is a primary concern in the assessment of long-term implications because it is linked directly to the performance-related criteria. Of all the criteria, the U-value criterion, can add the most significant thermal load to heat loss calculations, as previously indicated in Table 4-5. The assessment component of this step therefore addresses heat loss through conduction and approximates the difference in energy costs resulting from changes in the U-value of submitted windows. The effect of the difference in values is automatically retrieved from the DST based on the specified surface areas of the building and the window-to-wall ratio (WWR). Compensation (or cost savings with respect to energy) is suggested in an amount that will cover the annual difference between the required and borderline values for a specific period of time and at a given interest rate. Details about other considerations, such as regular maintenance and part replacement, are provided by the contractor for each borderline option in order to facilitate the decision process and complete this step.

The annual difference in energy consumption (referred to as the annuity) is calculated as the difference between the energy cost resulting from the use of the submittal item and that associated with the required (specified) one, as follows:

$$A = E_{total.Sub} - E_{total.Req} \tag{5-1}$$

where:

A is the amount of the annual difference in energy consumption, in dollars;

$E_{total.Sub}$ is the annual cost of energy resulting from the use of the submittal item, in dollars;

$E_{total.Req}$ is the annual cost of energy resulting from the use of the required item, in dollars.

The assignments $E_{total.Sub}$ and $E_{total.Req}$ are calculated using equation (4-8).

The long-term implications of the change in energy costs (compensation) is the present value of the amount of money that could be spent on building operation for a specific period of time and at a given interest rate. This amount is known as the present worth, and is calculated as follows:

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \tag{5-2}$$

where:

P is the present worth, in dollars;

A is the difference in charges between the required value and a borderline option, in dollars;

i is the interest rate;

n is the number of years of operation.

5.3.2.3 Reporting and Updating

During the "Reporting" step, all information about the borderline submittals that has been accumulated from the previous steps is presented in a final report, for which final approval is determined. The decision maker is a key player in the approval of the best option for the project based on the particular characteristics of the project and the final report. If technical issues are a priority for a project, then the option with the best MAUT and AHP scores should be selected, while an option associated with minimal time implications would be the optimal selection for projects that entail tight schedules. Once approval has been obtained, the framework updates the final submittal in the BIM platform to complete the "Updating" step of this phase. The updated submittal replaces the existing submittal, and all related drawings and specification data are updated accordingly in the BIM. The final action in this step is the recording of the details of the approved submittal in a customized submittal log so that the history of the project submittals can be tracked and verified.

The framework is designed to enhance and facilitate decision making during the submittal evaluation process rather than to provide solid or exact solutions for specific scenarios. It allows project parties, including contractors and consultants, to efficiently perform the evaluation process in a speedy and structured manner as a means of determining a final decision that best ensures the successful delivery of the project.

5.4 Implementation and Sample Application

During the development of a prototype system for this research, Revit Architecture 2011 was used as the BIM platform due to its popularity, ease of use, and programmability. The Revit Application Programming Interface (API) was used to customize and integrate Revit with MS Excel 2010 (the DST employed in this research) in order to dynamically retrieve, report, and update project data in BIM. The main programming environment employed was MS Visual Studio 2012, which uses the C# programming language and provides the necessary connections to enable Revit to communicate with MS Excel. Appendix D includes samples screenshots of the code as written in MS Visual Studio. The Revit communications are enhanced through customized interfaces launched via a customized add-in button created and coded conveniently in Revit. The evaluation process is performed in Revit through these interfaces. The implementation media utilized in the framework are illustrated in Figure 5-4.

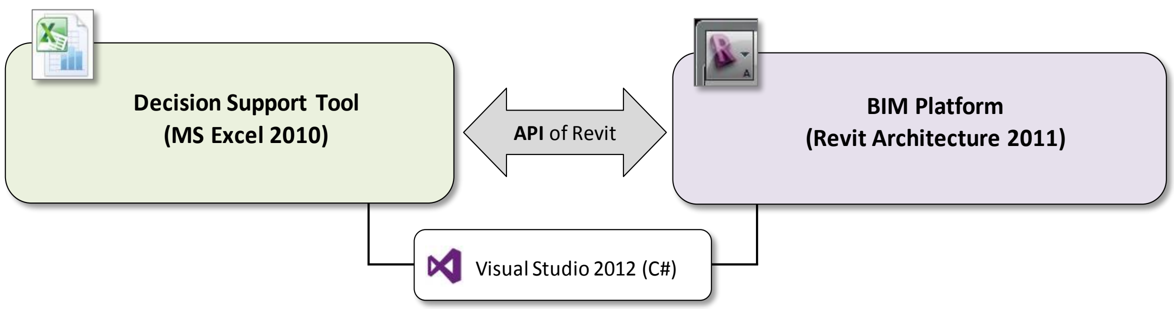


Figure 5-4: The Implementation Media for the Framework

The prototype system was implemented for the evaluation of window submittals that included minor deviations from the required specifications. The utility functions, design rationale, and performance-related criteria are discussed with respect to a hypothetical case study. The developed system can be expressed as a flow chart model that illustrates the workflow for the evaluation and approval of a submittal option, as shown in Figure 5-5.

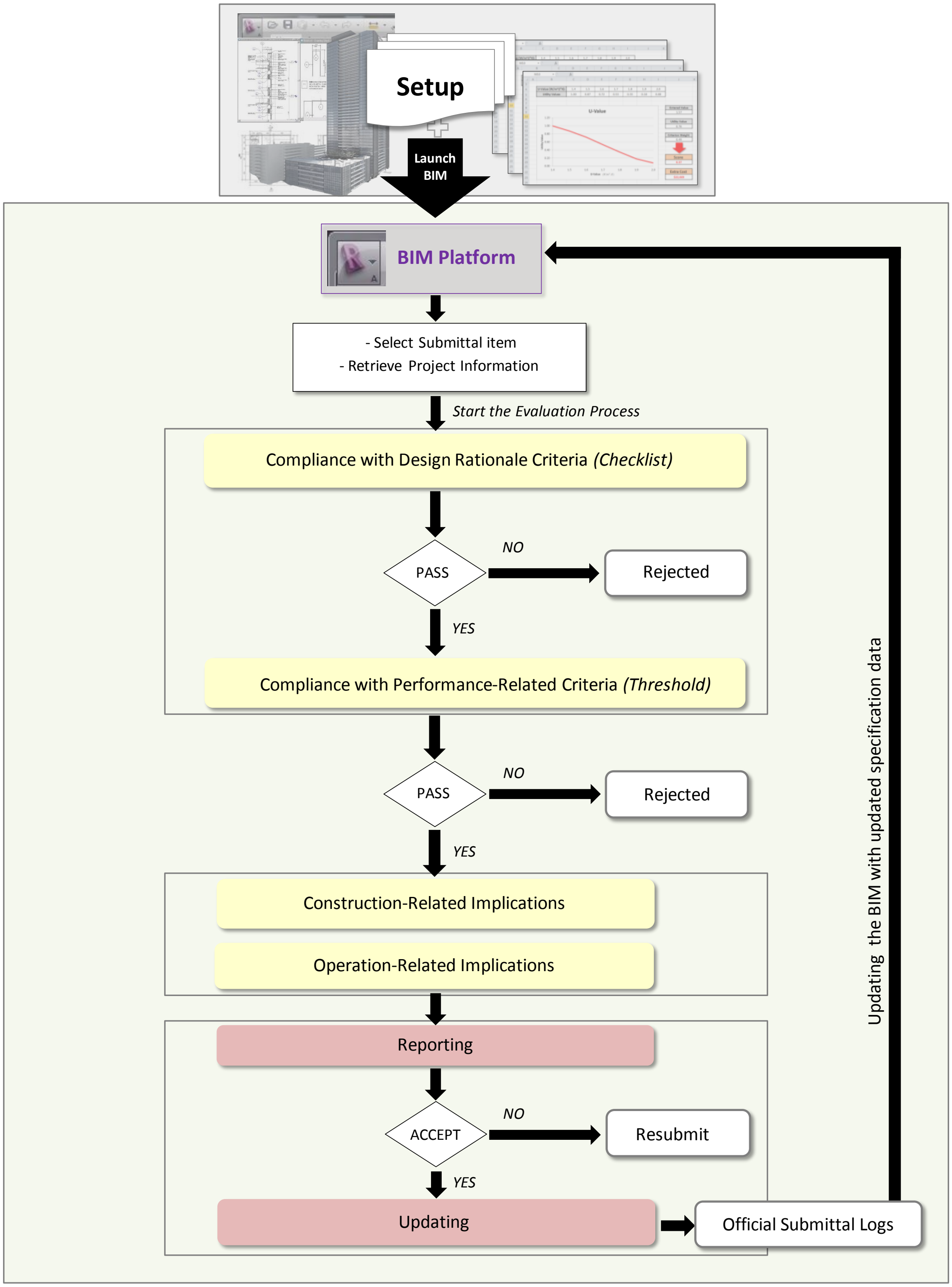


Figure 5-5: Flow Chart for the Developed System

The parameters of the case were compared with the default requirements that have been defined based on the performance-related criteria discussed in Chapter 4. The purpose of conducting this illustrative case study was to demonstrate the benefits of applying the developed BIM-based decision support system, which enables a best-value option to be determined systematically in an efficient and speedy manner with minimum subjectivity, in this case, for a three-option submittal for a high-rise building.

In the sample case study, a contractor examines three window options that are readily available in the market. Each option entails a slight violation of some of the required window criteria. Because obtaining the exact item specified could delay the project and affect the smooth progress of its final delivery, the contractor is interested in evaluating the conditions for accepting the other options. The building under study is a 19-storey commercial office building (57 m in height) that comprises 8,000 m^2 of surface area, including walls and windows, and 1,200 m^2 of roof. The window-to-wall ratio (WWR) for the building is assumed to be 0.60. The Setup phase has already been performed so that the threshold, utility functions, weights, and acceptance conditions have been established in MS Excel, and the evaluation criteria have been added in Revit. The system is thus ready for implementation.

Project Information: To start the evaluation process, the contractor launches the BIM platform (Revit), selects the window object under evaluation, verifies its shape and dimensions, and activates the evaluation process through the add-in button. The evaluation process begins with a submittal initiation interface where a variety of information must be provided, including general information, authentication, and item references. Figure 5-6 shows the Revit add-in button that launches the evaluation process and the submittal initiation interface.

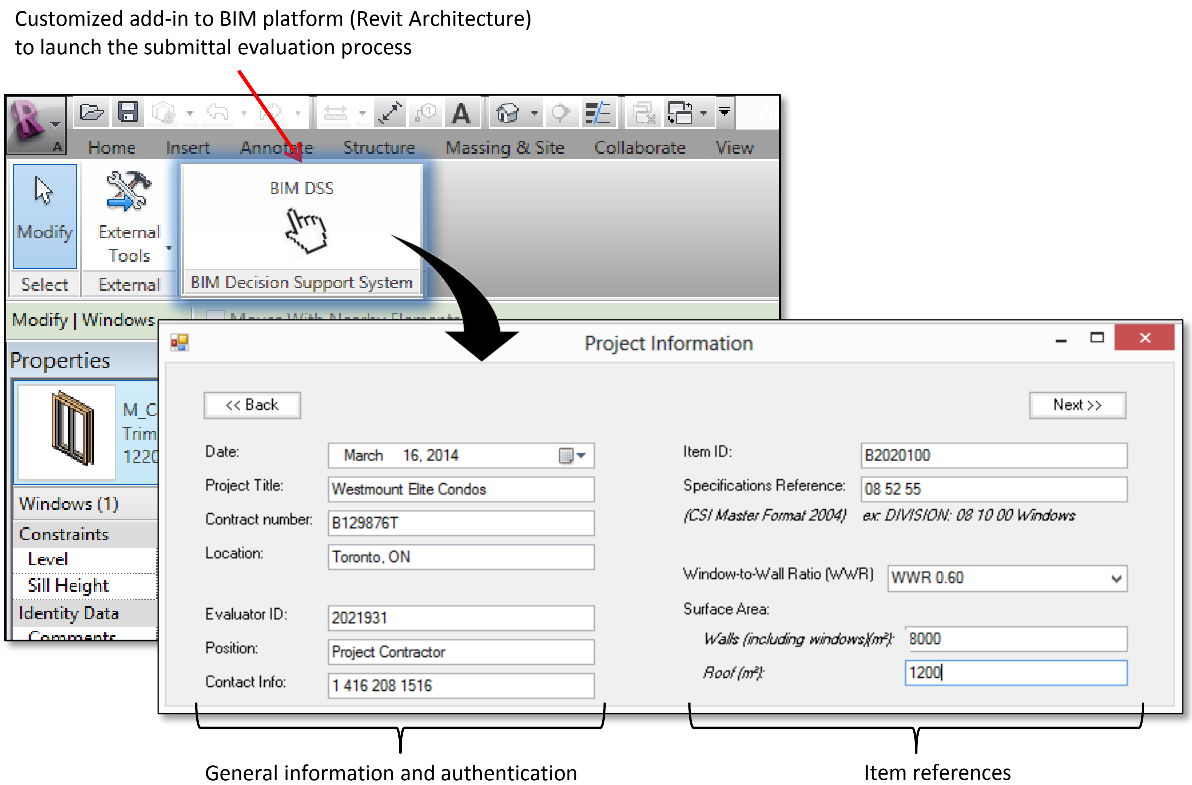


Figure 5-6: Sample Submittal Initiation Interface

As shown in Figure 5-6, the project is located in Toronto, information that is utilized for the retrieval of the appropriate HDDs and CDDs. The user must supply the surface areas of the walls and roof as well as the WWR so that the total surface area of windows with respect to the walls can be calculated to provide data that is essential for the heat loss calculations. In this case, the WWR is assumed to be 0.60. Once the project information has been entered, the evaluation process can be initiated by the user (contractor).

Compliance Check: The first step in the evaluation process is to check for compliance with the design rationale. Each of the three submittal options is assessed for compliance based on a simple checklist of Yes/No answers. The determination of the final score for each option is facilitated by a customized button that reflects the level of compliance for each option.

For an option to pass this step, it must exhibit full compliance: 100 %. Figure 5-7 shows a sample interface that enables the item to be checked for compliance against the stored design rationale criteria.

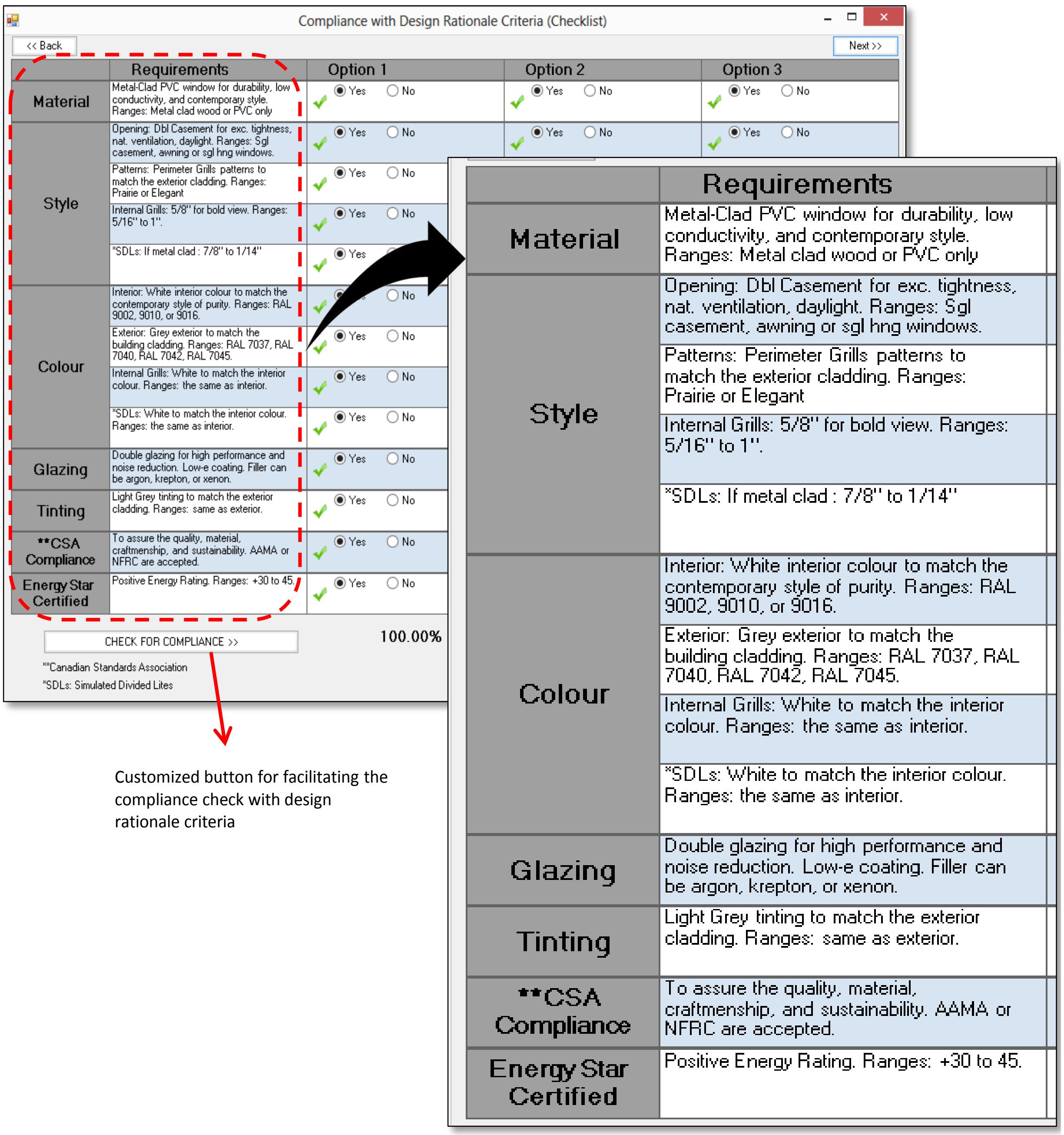


Figure 5-7: Sample Interface for Checking Compliance with the Design Rationale

The design rationale criteria for windows, as shown in Figure 5-7, include material, style, colour, glazing, tinting, CSA compliance, and Energy Star certification. These criteria capture subjective and qualitative aspects of a submittal evaluation that are omitted from even well-documented building designs. For example, the design rationale for colour has been specified as white in the interior to be consistent with the contemporary style of the interior design because white suggests purity and clean finishing. The acceptable ranges for this criterion are set to be RAL 9002, 9010, or 9016, according to European standards. The exterior colour of the frame has been selected to be grey to match the cladding material of the building with an acceptable range of RAL 7037 to 7045. This simple approach of storing and checking design rationale criteria effectively ensures that items selected throughout the construction process are consistent with the architectural design.

In this example, all three submittals are assumed to be thoroughly compliant with the design rationale criteria. The process therefore continues to the next step, which involves checking for compliance with performance-related criteria. In this step, the user must provide, through an activated interface, the technical specifications for the proposed submittals (options) as listed on the CSA certified window labels. When the user enters a value for a criterion, the system automatically calculates the score for that entered value in a hidden score spreadsheet from which the utility values and the AHP weights are retrieved. The summation of all scores retrieved is presented as a performance percentage that must be greater than or equal to the predefined acceptance threshold. In this scenario, the acceptance threshold is set to be 76 %, as suggested by practitioners. Figure 5-8 shows the score spreadsheet for the U-value criterion, the utility function developed as explained in Chapter 4 (Table 4-7), the value entered for the proposed submittal (i.e., Option 1) as provided by the user, and the equivalent utility value for the U-value entered.

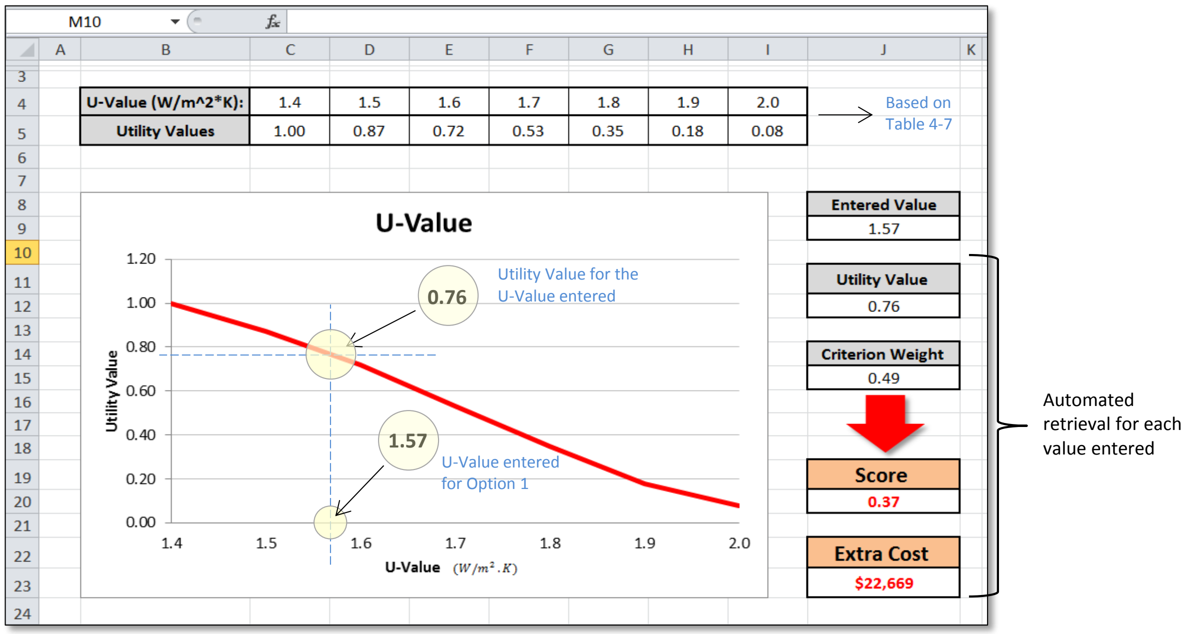


Figure 5-8: Score Spreadsheet for the U-Value Criterion

In this example, the contractor is submitting a window with a U-value of 1.57 W/m^2.$^\circ$K, which is equivalent to a utility value of 0.76. The AHP weights are predefined for each criterion in the Setup phase and are not dynamically changed with any adjustment in the values entered for each option. For the U-value criterion, the assigned weight is 0.49. Option 1 is thus assigned a score of 0.37. The extra cost associated with this criterion is calculated according to the heat loss calculations discussed in Chapter 4. The additional cost for this case study is explained below in the discussion of the step involving the assessment of implications.

The same score spreadsheet is prepared for the other four criteria: air infiltration, water penetration, visible transmittance (VT), and solar heat gain coefficient (SHGC). Figures 5-9, 5-10, 5-11, and 5-12 illustrate the score spreadsheets for the four criteria, respectively, including the utility functions generated as described in Chapter 4, and the values entered for each criterion for Option 1.

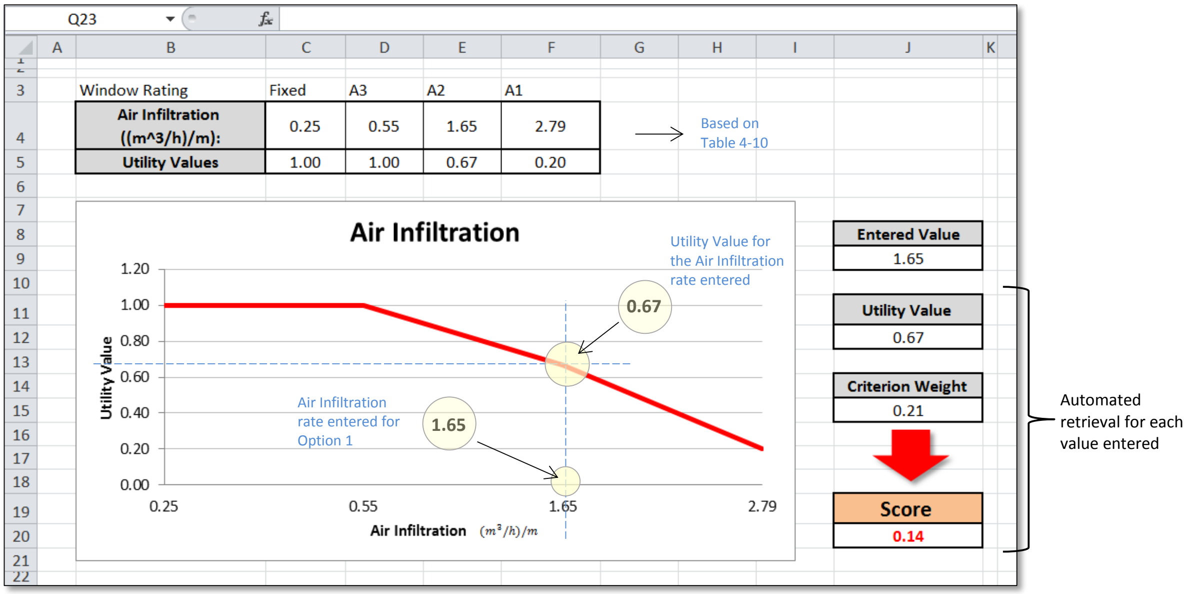


Figure 5-9: Score Spreadsheet for the Air Infiltration

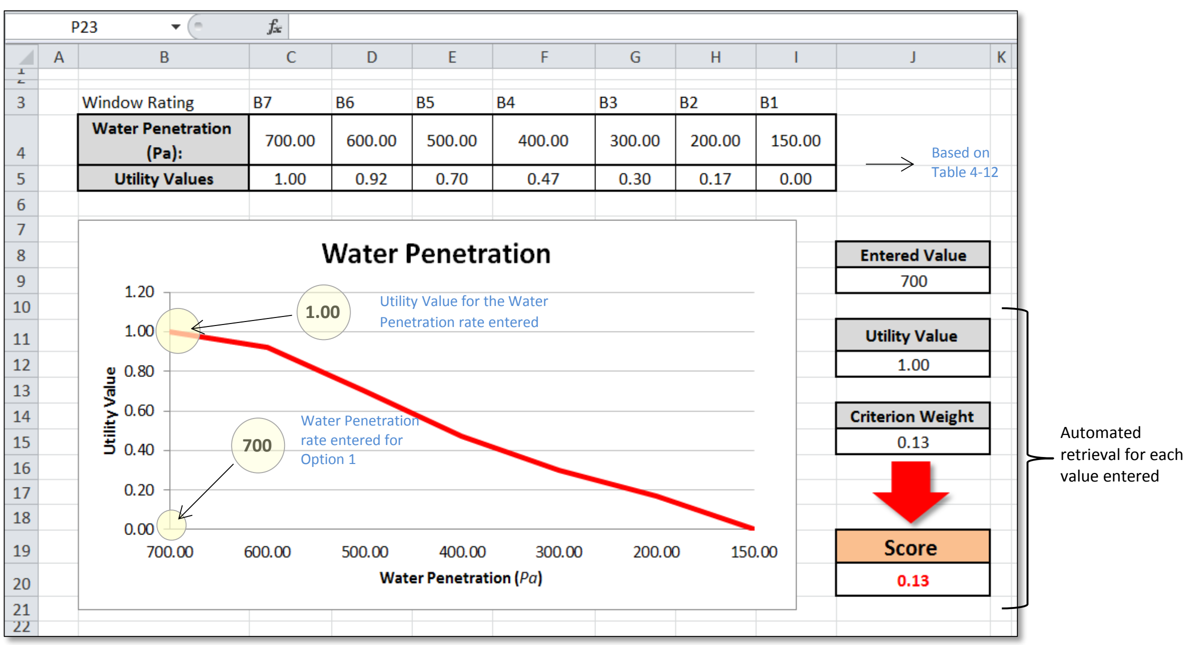


Figure 5-10: Score Spreadsheet for the Water Penetration

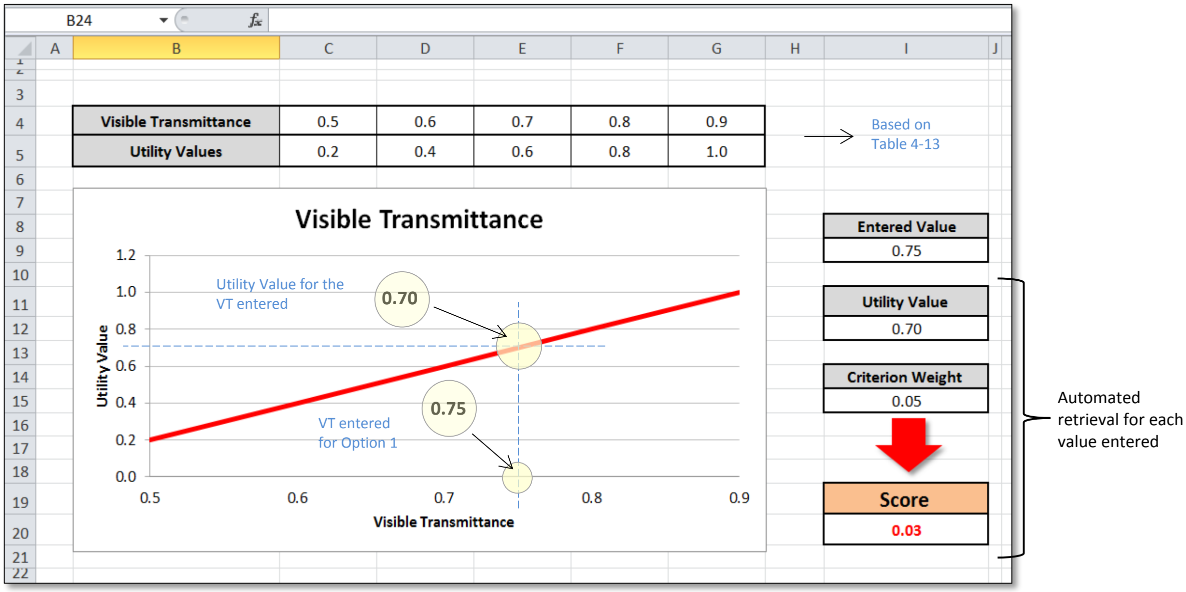


Figure 5-11: Score Spreadsheet for the Visible Transmittance (VT)

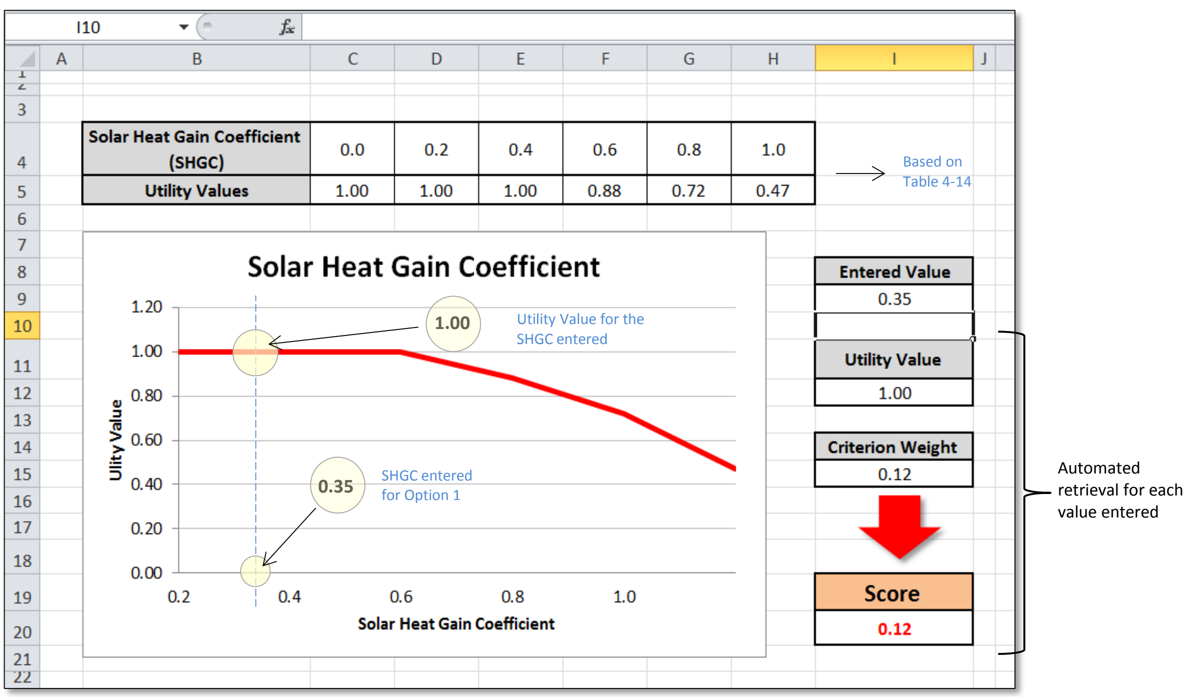


Figure 5-12: Score Spreadsheet for Solar Heat Gain Coefficient (SHGC)

Once the user has entered all of the values for the performance-related criteria for the three window options, the system sums the scores for each criterion associated with each option and then provides a total score that indicates the overall performance level. This task is facilitated through a customized button that has been added to the interface so that the user can check whether each option complies with the minimum acceptance threshold. The interface where the performance levels for the three options are checked and a sample calculation of the performance level for Option 1 are illustrated in Figure 5-13.

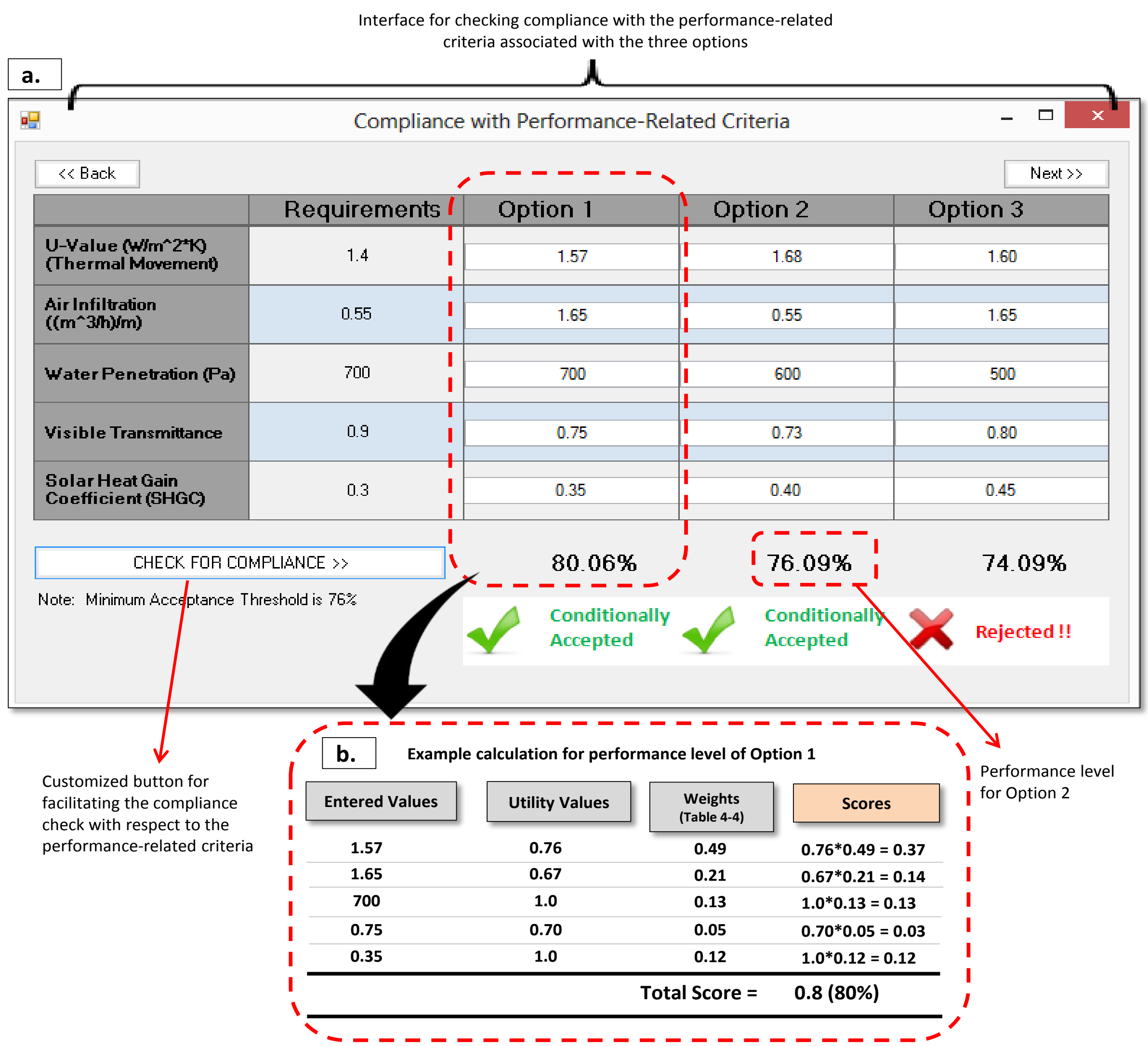


Figure 5-13: Sample Check for Compliance with Performance-Related Criteria

As shown in Figure 5-13a, the interface for checking compliance with performance-related criteria lists the five technical properties for the three window options and their automatically calculated scores (performance levels) as compared against the requirements. Based on an acceptance threshold of 76 % for overall performance, Option 1 and Option 2 were determined to be conditionally accepted (borderline submittals) while Option 3 was rejected. The sample calculation shown in Figure 5-13b explains the calculation of the total performance level for Option 1. The same approach is utilized for determining the performance levels for Options 1 and 2.

Assessment: The next step for the two borderline submittals is "Impact Assessment." In this step, the borderline items are assessed with respect to construction and operational implications. The construction implications are provided by the contractor, and the operational implications of changing the U-value can be computed as the cost of the additional energy consumption associated with a lower-quality window, the calculation of which is dependent on factors such as surface area, heating degree-days (HDDs), cooling degree-days (CDDs), and the price of natural gas/electricity. The cost of energy consumption for heating and cooling can be estimated, and the annual energy cost (E_{total}) is then the summation of $E_{heating}$ and $E_{cooling}$. The additional operational costs associated with the acceptance of windows with lower U-values are estimated based on equations (5-1) and (5-2). Table 5-3 details the sample energy calculations for the borderline submittals (Option1 and Option 2), based on the amount by which building operation costs would increase over a specific time period and at a given interest rate: in this case, 10 years and 3 %.

Table 5-3: Ten-Year Energy Costs for the Sample Borderline Submittals

WWR 0.60			As Specified	Borderline Submittals	
				Option 1	Option 2
Components	Surface Area (m^2)		U-value ($W/m^2.K$)	U-value ($W/m^2.K$)	U-value ($W/m^2.K$)
Walls	3,200		0.21	0.21	0.21
Windows	4,800		**1.40**	**1.57**	**1.68**
Roof	1,200		0.40	0.40	0.40
Total Suface Areas :	**9,200 m^2**	Cost of Heating ($E_{heating}$) eq. (4-4)	$14,024	$15,477	$16,418
		Cost of Cooling ($E_{cooling}$) eq. (4-6)	$11,613	$12,817	$13,596
		Annual Cost of Energy Consumption (E_{total}) eq. (4-8)	**$25,637**	**$28,295** **9.3 %** *difference*	**$30,014** **14.5 %** *difference*
		Extra Operational Cost (P) (10 years and 3% interst rate) **eq. (5-2)**	N / A	**$22,669**	**$37,337**

As shown in Table 5-3, the annual energy cost with the specified U-value is about $25,637. This amount increases when windows with poorer U-values are substituted. For example, the annual energy cost can reach about $28,295 for a window with a U-value of 1.57 W/m^2.$^\circ$K, which represents an annual difference of $2,658, or 9.3 %. Assuming 10 years of operation and a 3 % interest rate (i.e., present worth), the additional operational cost would be approximately $22,669, which would rise to $37,337 if Option 2, with 1.68 W/m^2.$^\circ$K, is approved.

Construction implications involve requirements for additional installation/handling fees, extra delivery time, and changes in price. For this case, according to contractor input, the construction impact is negligible and will be absorbed by the contractor. The main operational effect is the additional cost of energy attributable to the differences in the U-values of the borderline submittals, which represent the degree of conduction. The interface that summarizes the implications associated with the two borderline submittals is shown in Figure 5-14.

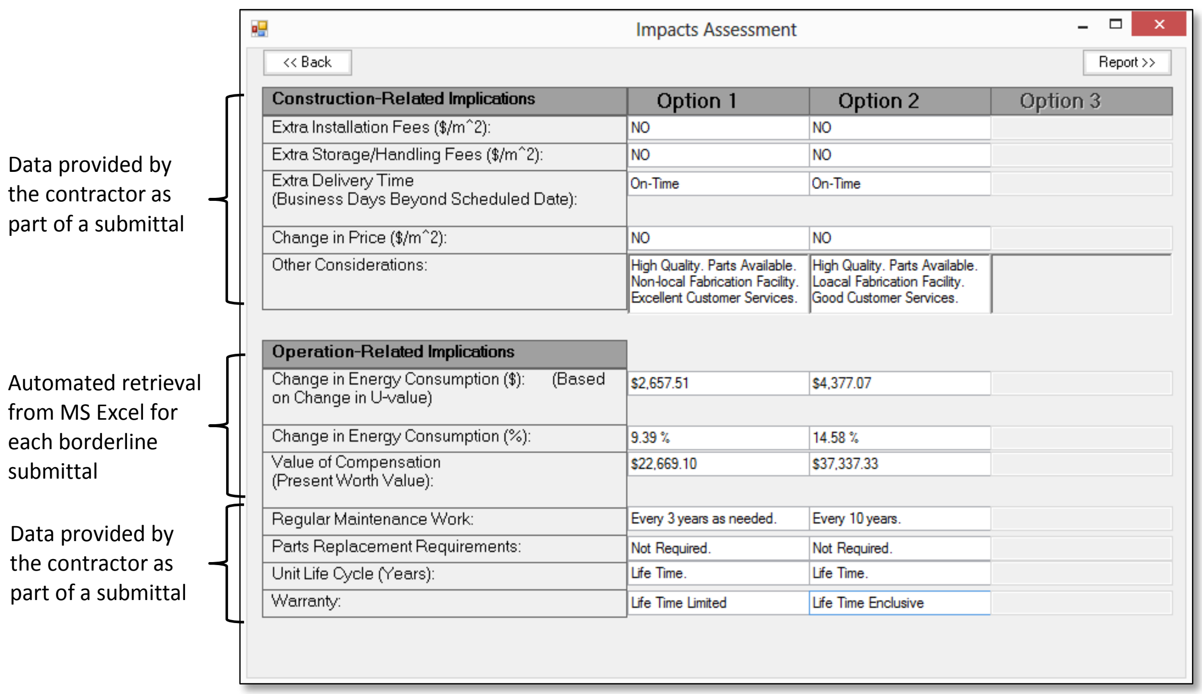


Figure 5-14: Sample Impact Assessment Summary

For the sample case, based on the assessment results indicated in Figure 5-14, Option 2 appears to involve greater cost increases than Option 1 over the long term: $37,337 and $22,669, respectively. Submitting an item with a U-value of 1.68 (Option 2), which is only 0.28 lower in performance than the specified value, results in approximately 14.5 % additional annual energy consumption costs: $4,377 more per year. In this example, the proposed BIM-based system suggests that these two options could be acceptable but that the owner will need compensation equal to the additional energy cost: $22,669 for Option 1 or $37,337 for Option 2.

Reporting and Updating: After all of the implications of the submittals have been presented for review and consideration, a final report is produced to provide assistance with the determination of the best-value option. Figure 5-15 shows a sample final report that summarizes the information needed for negotiation and decision making, including general information, compliance, and associated implications.

Figure 5-15: Sample Final Report

As shown in Figure 5-15, Option 1 scores better with respect to overall performance (80 %) than Option 2 (76 %). While Option 2 is associated with greater total implications, it also requires less maintenance work over the long run. The best value for the project should be selected based on consideration of the output from the system. For this case study, Option 1 was selected because project performance is critical and therefore the highest priority. After the selection of an appropriate option, the final phase is the "Reporting and Updating" step: the approved submittal is dynamically updated in Revit and recorded in the submittals log. Figure 5-16 shows the recorded details of the approved submittal in the submittal log.

BIM-Based Decision Support System - Submittal Log

Project Title	Westmount Elite Condos							
Contract #	B129876T							
Date	Location	Evaluator ID	Contact info.	Iitem ID	Specification Reference	Status	Updates	
3/28/2014	Toronto, ON	2021931	1 416 208 1516	B2020100	08 52 55	**Option 1** Approved (80%)	U-Value:	1.57
							Air Infiltration:	1.65 (A2)
							Water Penetration:	700 (B7)
							VT:	0.75
							SHGC:	0.35
							Extra Construction Cost:	Covered
							Operational Compensation:	$22,669

Figure 5-16: Updated Submittal Log

5.5 Conclusion

This chapter has introduced the developed decision support framework, including an outline of the conceptual approach and the two phases involved in its development: the framework setup and the submittal evaluation process. Each step in both phases has been explained in detail. The first step, the Decision Support Tool Setup, enables the project manager to provide specific information about a project. The BIM Setup entails customizing the BIM to accept two types of input parameters relevant to window submittals: qualitative design rationale criteria and quantitative performance-related, or technical, criteria. During the Compliance Check step, submittal options are evaluated qualitatively against a checklist of acceptability and tolerance ranges, and quantitatively in comparison with specified acceptance thresholds. The Impact Assessment step then evaluates the life cycle cost of submittals to determine the conditional acceptability of the borderline submittals, based on consideration of construction and operational implications that result from the short- and long-term deviations from the original specifications. A recommended decision is then offered for review by the user. In the last step, the final choice is recorded, and the data associated with the submittal are then updated. The application of the framework has been demonstrated through a detailed description of the use of a prototype system for a sample case study. The results presented confirm that the framework should prove to be a valuable asset, providing an efficient, automatic, structured method for the evaluation of submittals.

Chapter 6

Sensitivity Analysis

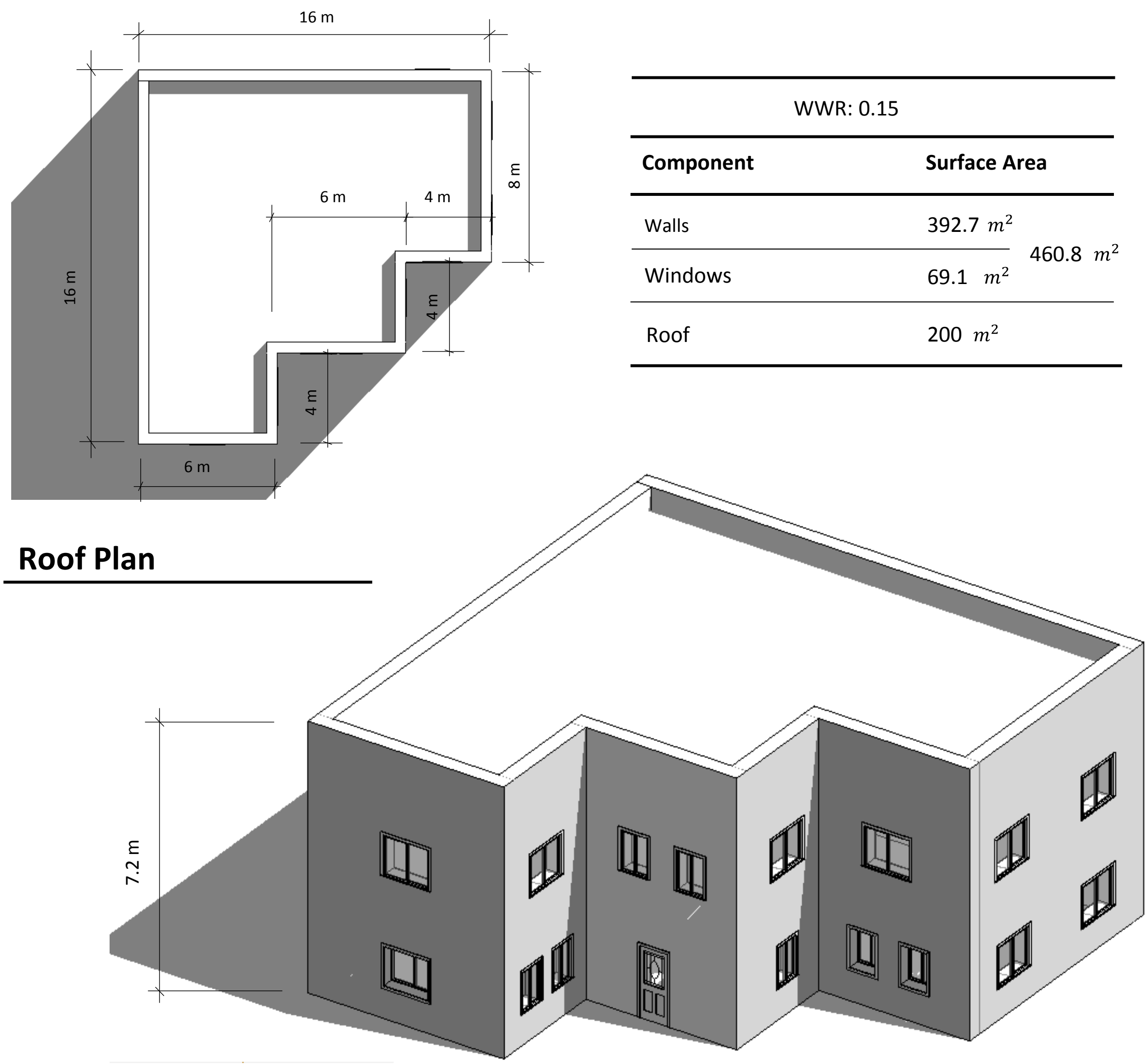
6.1 Introduction

This chapter presents the implementation of the developed prototype BIM-based decision support system for a close-to-real-life case study: one unit of a housing complex project. The evaluation process for three assumed window submittal options that entail minor changes is described as a means of demonstrating the automated mechanism that produces a final recommendation. As part of the decision process, a sensitivity analysis for conditionally accepted (borderline) options has been incorporated to enable a determination of the relationship between changes in the characteristics associated with the submittal characteristics and the acceptance condition. Accordingly, distribution for submittal acceptance is expressed to facilitate decisions related to submittal finalization.

6.2 Case Study

The developed prototype system has been applied to a close-to-real-life case study that transpired during the data collection exercise at Umm Al-Qura University (UQU) in Saudi Arabia. The case study involves the evaluation of three window options that the contractor submitted during the course of the construction of a faculty housing project. The project represents one component of the new $258 million UQU campus development, which has been underway since 2008 and involves the construction of five buildings: facilities for engineering, education, and management; an educational hospital; and faculty housing.

The faculty housing project entails the construction of 60 detached units to be completed in three phases during 2014. The footprint of each two-storey unit is 200 m^2 (12,000 m^2 in total), with a total wall surface area of 460.8 m^2. The combined surface area of the windows represents only 15 % of the total, giving a window-to-wall ratio (WWR) of 0.15. The contemporary-style housing concept was designed to provide a high level of enclosure performance appropriate for the harsh, hot, dusty Saudi Arabian weather. Figure 6-1 illustrates the 3D-BIM conceptual model of one of the faculty housing units.



WWR: 0.15		
Component	**Surface Area**	
Walls	392.7 m^2	460.8 m^2
Windows	69.1 m^2	
Roof	200 m^2	

Figure 6-1: BIM Conceptual Model of a Faculty Housing Unit

The windows for each unit were architecturally designed to be double slider windows because of the daylight and natural ventilation they provide and because they are easy to clean and maintain. For noise reduction and privacy, double glazing and reflective exterior tinting were also specified. A beige frame colour and aluminum-clad PVC materials were suggested based on their neat finishing and durability. The technical specifications included resistance to temperatures up to 70 °C (assumed to be equivalent to utilizing a window with a U-value of 1.4 $W/m^2.^{\circ}K$) and a maximum allowance of 0.55 $(m^3/h)/m$ (equivalent to a CSA-A440 A3 rating). Although the region is subject to occasional heavy rain and persistent moisture, the water penetration criterion is only roughly specified, and in any case, the UQU project management department always requires the highest water penetration rating. Visible transmittance (VT) and solar heat gain coefficient (SHGC) constraints are not provided in the specifications. To overcome the problem of missing information, the default requirements were used as a basis of comparison.

Setup: As proposed in this thesis, the setup phase of the system is completed before the initiation of the submittal evaluation process. The predefined default evaluation criteria, the assigned weights, the utility functions generated, and the acceptance conditions had already been approved by the UQU and were thus available to be utilized in the decision support tool (DST). The suggested minimum acceptance threshold was set at 80 %: any submittal with a performance level less than 80 % would be rejected.

As part of the BIM Setup step, the BIM conceptual model was generated, customized, and fed with all of the evaluation criteria, including both design rationale and performance-related criteria. Figure 6-2 shows the customized fields for specifying the window “Properties” so that all of the evaluation criteria could be stored and documented. Once the Setup phase was completed, the BIM model could be utilized for the evaluation of the three window options submitted by the contractor.

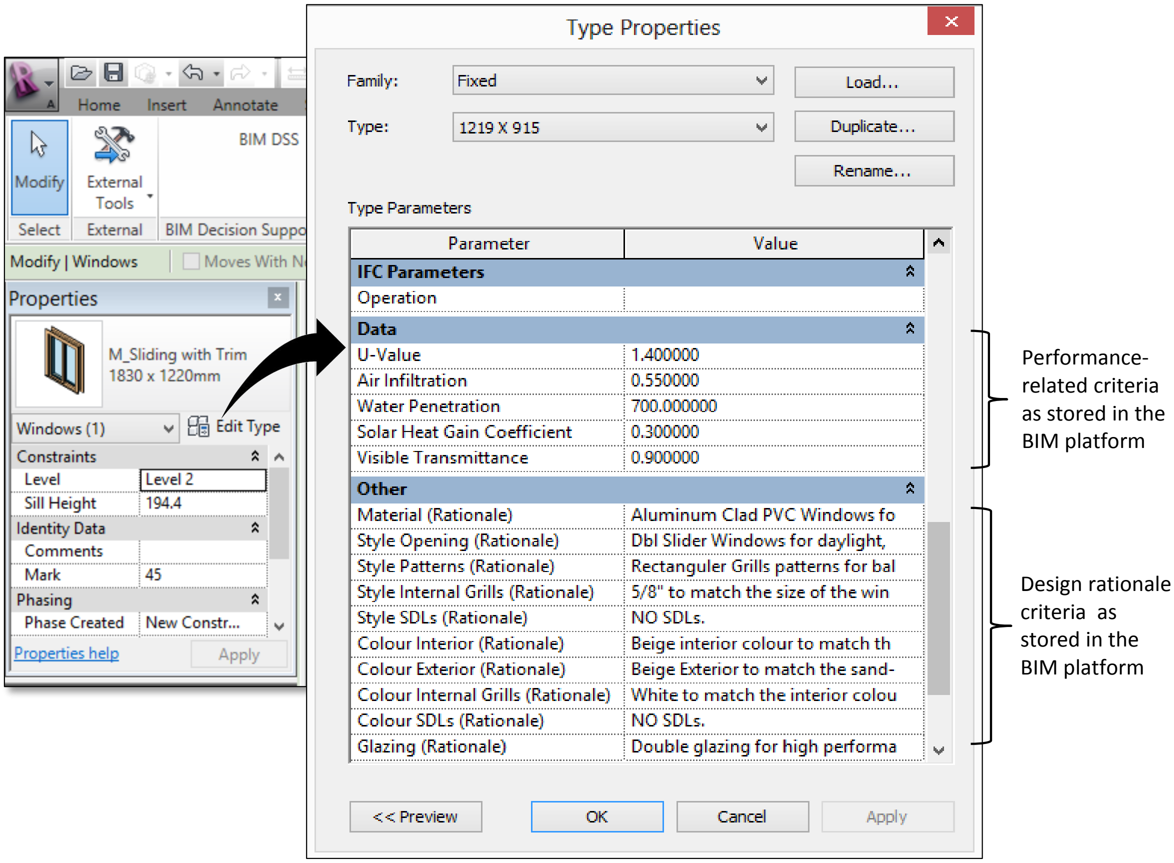


Figure 6-2: BIM Setup with All Evaluation Criteria

Project information: To start the evaluation process, the consultant launches the BIM platform (Revit), selects the window object under evaluation, verifies its shape and dimensions, and activates the evaluation process through the add-in button. Prior to the actual evaluation process, the consultant provides the information requested through a submittal initiation interface: general information, authentication, item references, and other details. Figure 6-3 shows the submittal initiation interface for the case study, as launched by the Revit add-in button.

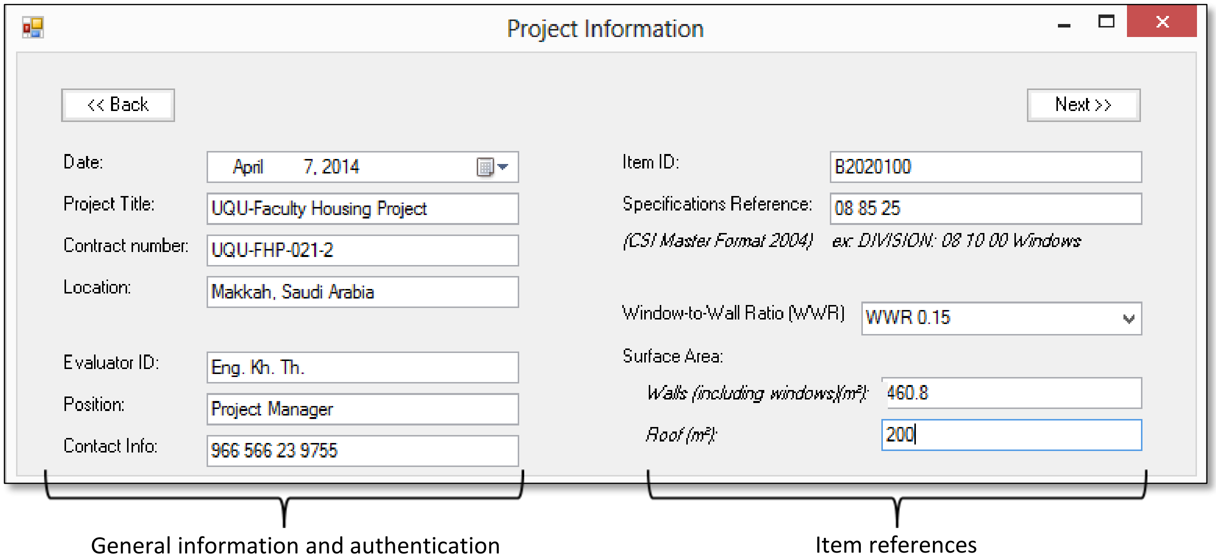


Figure 6-3: Interface for Submittal Initiation

In this case, the data entered by the consultant indicates the location of the project in Makkah, Saudi Arabia; the surface areas of the walls and roof; and the WWR. Once the project information has been entered, the evaluation process can be initiated by the user (consultant).

Compliance Check: The first step in the evaluation process is to check for compliance with the design rationale. Each of the three submittal options is assessed for compliance based on a simple checklist that asks for Yes/No answers. The determination of the final score for each option is facilitated by a customized button that calculates and displays the level of compliance for each option. For an option to be assessed as successful in this step, it must exhibit full compliance: 100 %. In this case, two options were thoroughly compliant with the design rationale criteria while the third, only partially compliant, option (Option 2) was rejected because it suggested the use of a single-glazed window that is not certified according to the CSA or any other acceptable standard. Figure 6-4 shows a sample interface for checking the item for compliance with the stored design rationale criteria; the rejected option is clearly indicated.

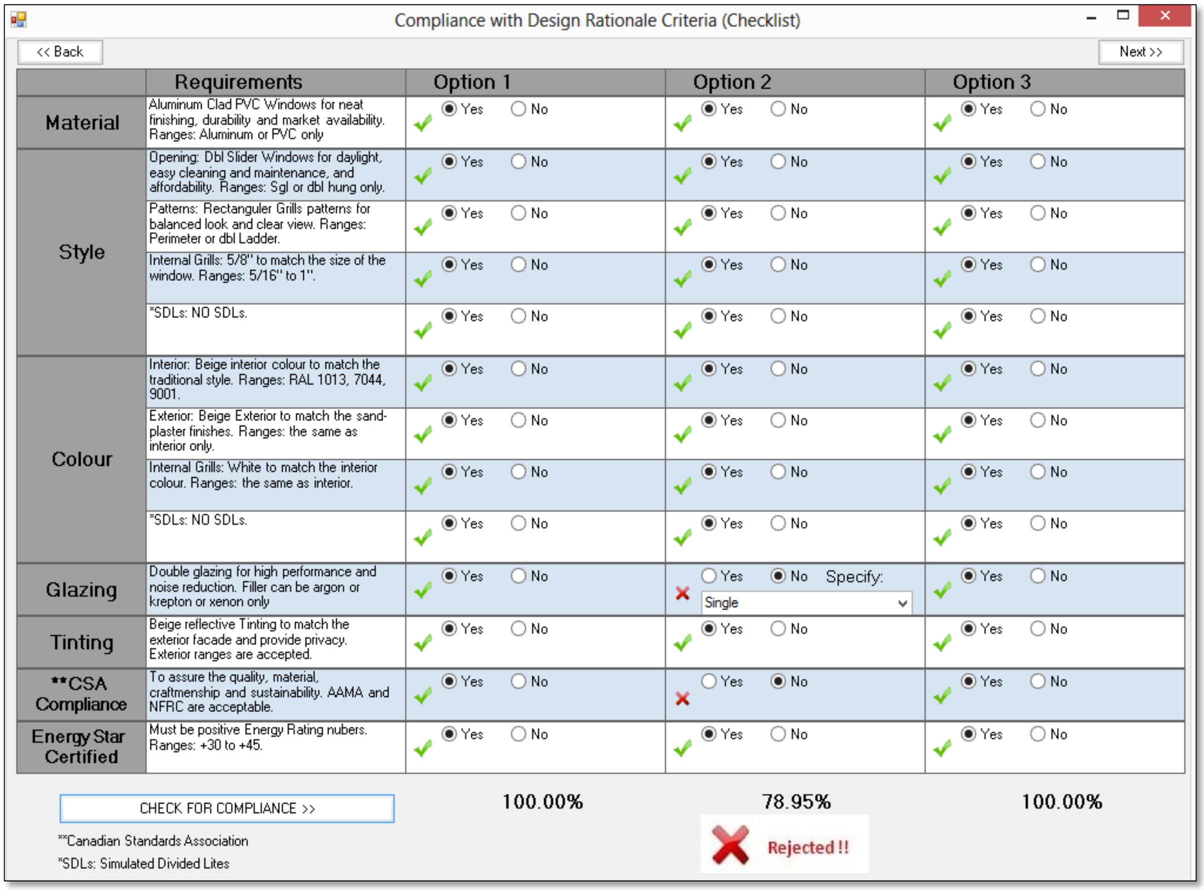


Figure 6-4: Interface for Checking Compliance with the Design Rationale

The next step involves checking for compliance with performance-related criteria. In this step, the user employs an activated interface to stipulate the technical specifications for the proposed submittals (options) as provided by the contractor based on the window certification labels, as shown in Figure 4-1. The summation of all scores retrieved from the DST is presented as a performance percentage that must be greater than or equal to the predefined acceptance threshold: 80 %. In this example, the two remaining options submitted by the contractor have U-values of 1.60 W/m^2.$^\circ$K and 1.53 W/m^2.$^\circ$K, which are equivalent to utility values of 0.72 and 0.82, respectively. The weights are predefined for each criterion in the Setup phase and therefore do not change dynamically with any adjustment in the values entered for each option. For the U-value criterion, the assigned weight is

0.49 (Table 4-4), and the U-value criterion scores assigned for Option 1 and Option 3 are thus 0.35 and 0.40, respectively. The same method of score calculation is applied to the remaining performance-related criteria in order to obtain the final scores that indicate the overall performance level for each option. The compliance interface for checking the performance-related criteria for the two options is illustrated in Figure 6-5.

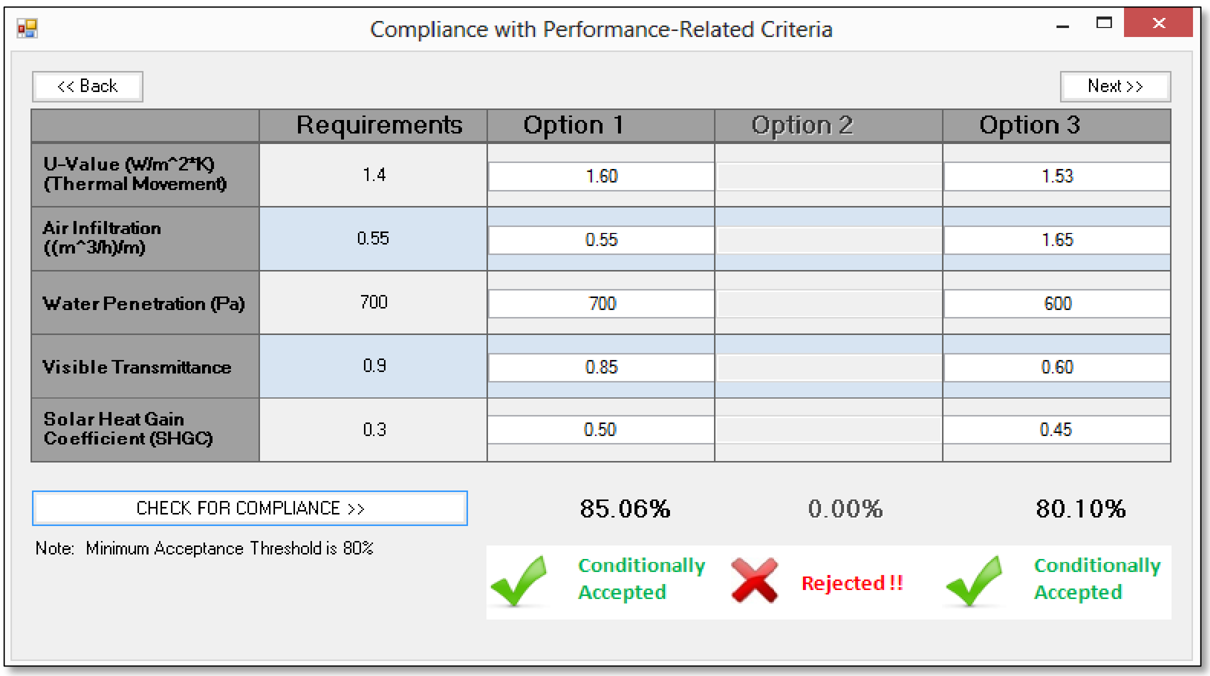


Figure 6-5: Interface for Checking Compliance with Performance-Related Criteria

As shown in Figure 6-5, the interface for checking compliance with performance-related criteria lists the five technical properties for the two window options along with their automatically calculated scores (performance levels) to be compared with the requirements. Based on an acceptance threshold of 80 % for overall performance, Option 1 and Option 3 were both determined to be conditionally accepted (borderline submittals), and the rejection of Option 2 was carried forward from the results of the previous step.

Assessment: The next step for the two borderline submittals is “Impact Assessment.” In this step, the borderline items are assessed with respect to construction and operational implications. The construction implications are provided by the contractor, and the operational implications of changing the U-value can be computed as the cost of the additional energy consumption associated with a lower-quality window, the calculation of which is dependent on factors such as surface area, heating degree-days (HDDs), cooling degree-days (CDDs), and the price of natural gas/electricity. Because the project is located in Makkah, Saudi Arabia, which is a hot, humid region, heating requirements are negligible (HDDs are zero) but cooling requirements are substantial. The CDDs for Makkah were computed to be 7549 (Al-Hadhrami 2013). The price of electricity is therefore a major factor for consideration in the calculation of the annual energy costs: 0.09 cent/kWh. The interface that summarizes the implications associated with the two borderline submittals is shown in Figure 6-6.

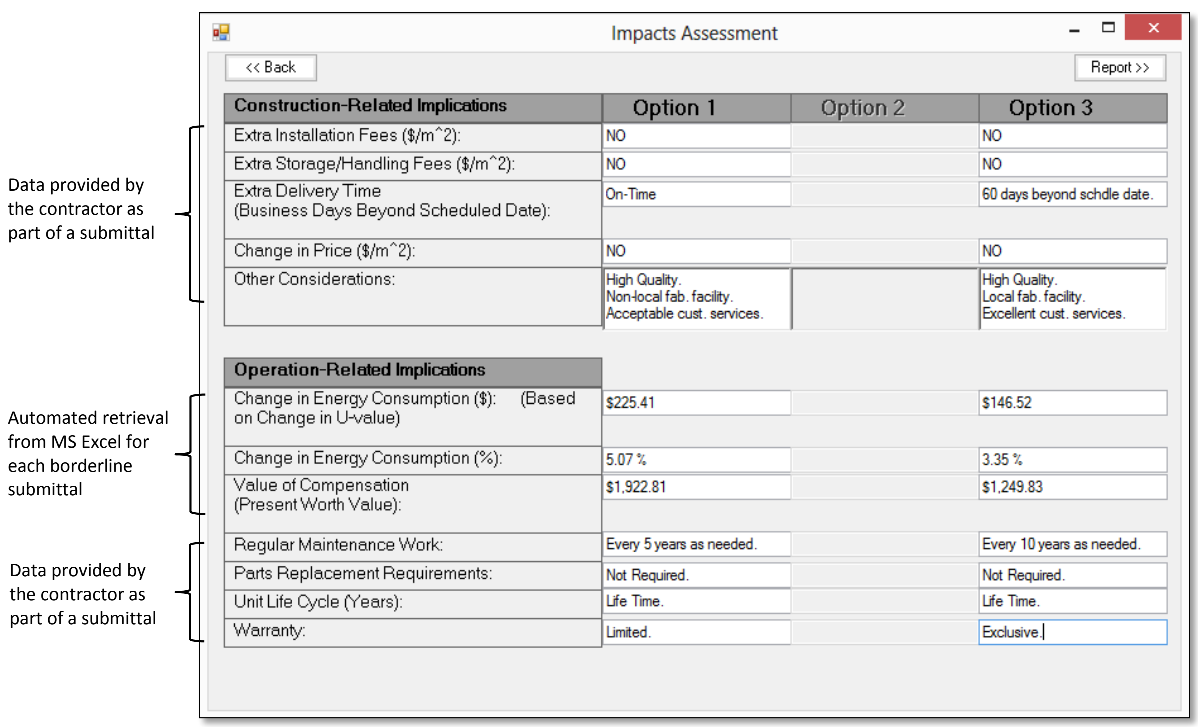


Figure 6-6: Impact Assessment Summary

Construction implications involve requirements for additional installation/handling fees, extra delivery time, and changes in price. For this case, according to contractor feedback, with Option 3, the construction schedule would be affected: the delivery time would increase by 60 days beyond the scheduled date. If this option were to be approved, any associated costs should be absorbed/covered by the contractor as a condition of acceptance.

The primary operational effect is the additional cost of energy attributable to the difference between the U-values of the borderline submittals, which represent the degree of conduction. As shown in Figure 6-6, the additional operational cost would be approximately $1,923 for a window with a U-value of 1.60 $W/m^2.^{\circ}K$, assuming 10 years of operation and a 3 % interest rate, based on present worth. If Option 3, whose U-value is 1.53 $W/m^2.^{\circ}K$, were approved, the additional operational cost would drop to $1,250. Since the project entails the construction of 60 units with the same configuration, Option 1 would impose additional costs of about $115,380 (approximately SAR 438,444) over the 10 years of operation and at the 3 % interest rate. Option 3, on the other hand, would involve about $75,000 (SAR 285,000) in extra operational costs.

Reporting and Updating: After all of the implications of the submittals have been presented for review and consideration, a final report is produced to support the determination of the best-value option. Figure 6-7 shows the final report that summarizes the information needed for negotiation and decision making, including general information, compliance results, and the associated implications. Option 1 has been assigned a better score with respect to overall performance (85 %) than Option 3 (80 %). While Option 3 is associated with lower total cost and maintenance implications, it requires more extensive delivery time, which might affect the project schedule. The best value for the project should be selected based on consideration of the system output. For this case study, Option 1 was selected in spite of the greater long-term associated costs because, for this project, time is critical and therefore the highest priority.

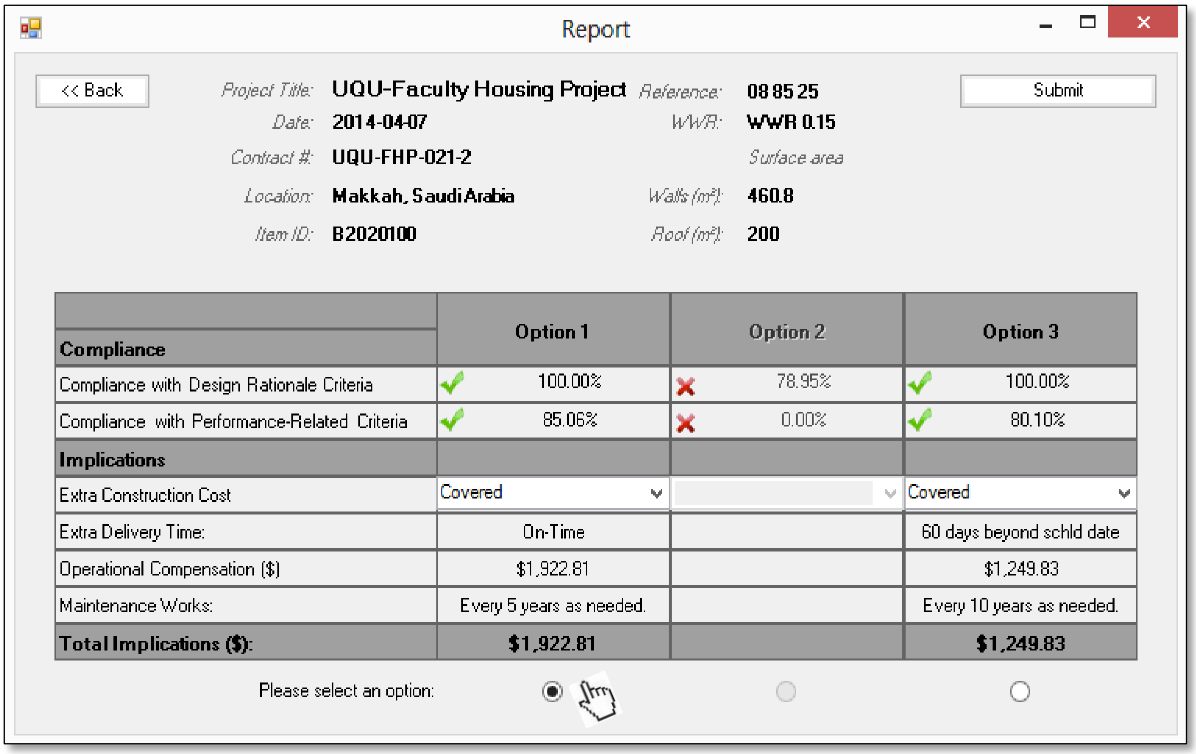


Figure 6-7: Final Report

After the selection of an appropriate option (Option 1), the final phase is the "Reporting and Updating" step: the approved submittal is dynamically updated in Revit with all of the new data and then recorded in the submittal log for future tracking and verification. Figure 6-8 shows the details recorded in the submittal log for the approved submittal. The implementation of the case study has demonstrated the importance of modeling and storing design rationale criteria and utilizing them as an essential factor in the submittal evaluation process. It has also shown the involvement of project parties in the systematic determination of the best-value option with minimum subjectivity and in a speedy manner that includes consideration of the organizational requirements and project constraints.

BIM-Based Decision Support System - Submittal Log

Project Title	UQU-Faculty Housing Project
Contract #	UQU-FHP-021-2

Date	Location	Evaluator ID	Contact info.	Iitem ID	Specification Reference	Status	Updates	
4/7/2014	Makkah, SA	Eng. Kh. Th.	966 566 23 9755	B2020100	08 85 25	**Option 1** Approved (85%)	U-Value:	1.6
							Air Infiltration:	0.55(A3)
							Water Penetration:	700 (B7)
							VT:	0.85
							SHGC:	0.5
							Extra Construction Cost:	Covered
							Operational Compensation:	$1,923 per unit

Figure 6-8: Updated Submittal Log

6.3 One-Parameter Sensitivity Analysis

To provide the contractor with a mechanism for understanding possible improvements that would render a submittal acceptable, a sensitivity analysis is conducted as part of the developed system. In the first attempted sensitivity analysis, changes in the score that a submittal achieves (and also the compensation that a submittal implies) are examined as a function of changes in the window parameters (performance-related criteria). The analysis is performed following a Monte Carlo simulation approach and was conducted for the case study described. The first experiments focused on changing only one window parameter. Since the U-value is the most influential parameter (the top-weighted criterion that imposes a significant thermal load with respect to the heat loss calculation), it is considered as an example. Table 6-1 lists nine sample scenarios, along with the evaluation result for each scenario (scores and compensation amount).

Table 6-1: Effect of Changes in the U-Value of a Window on its Score and Compensation

		Scenario no. 1		………………		………		…………		Scenario no. 9
(window's parameters)	**U-Value** $(W/m^2.K)$	**1.4**	**1.45**	**1.5**	**1.55**	**1.6**	**1.65**	**1.7**	**1.75**	**1.8**
	Air Infiltration	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
	Water Penetration	700	700	700	700	700	700	700	700	700
	Visible Transmittance	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Solar Heat Gain Coefficient	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Score (%)		100	96.82	93.63	89.96	86.28	81.63	76.97	72.56	68.15
Compensation ($)*		$0	$481	$961	$1,442	$1,923	$2,404	$2,884	$3,365	$3,846

*Based on the case study described in Section 6-2 (surface area of walls: 460.8 m^{2}; roof: 200 m^{2}; WWR: 0.15)

Each of the nine scenarios in Table 6-1 (columns 3 to 11) was created by changing the U-value within a practical range (1.4 W/m^2.°K to 1.8 W/m^2.°K) to simulate the fact that the contractor has various options in windows within that range. For the generation of these scenarios, all other parameters (rows 2 to 5) were kept constant (i.e., at the default requirements). Once these scenarios were created, they were assessed individually using the developed prototype system, and the values of the scores and compensation amounts were calculated accordingly, as indicated in the bottom two rows of the table.

The results shown in Table 6-1 reveal that the evaluation score for each scenario decreases with an increase in the U-value (poorer U-value) while the amount of compensation increases (poorer-quality windows perform less well and result in greater operational implications). This correlation is consistent with the fact that the U-value is a major factor in the calculation of heat loss (as explained in Chapter 4). Figure 6-9 shows a plot of the sensitivity analysis results with respect to the evaluation score and compensation amount.

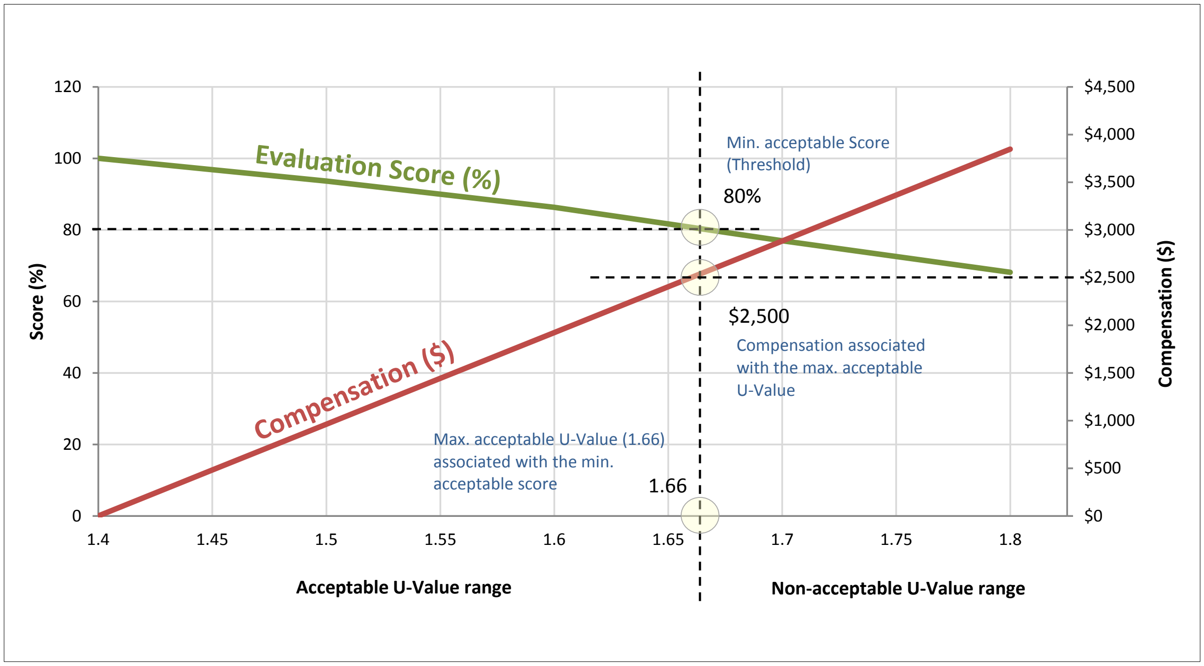


Figure 6-9: Score and Compensation Amount as a Function of U-Value

For an option to be considered a borderline submittal, it must satisfy the minimum acceptable threshold: for this case study, 80 %. According to Figure 6-9, an option can be assessed as borderline when it has a U-value no greater than 1.66 $W/m^2.^{\circ}K$, which is associated with operational compensation costs of about $2,500. Submitting items with superior U-values (less than 1.66 $W/m^2.^{\circ}K$) would result in the addition of options that have higher scores and fewer associated compensation costs. From another perspective, a submitted item whose score is equal to or greater than 80 % (threshold) would lead to enhanced U-value performance (i.e., 1.66 $W/m^2.^{\circ}K$ or less), which in turn, would require less operational compensation. Therefore, rejecting an item whose score is less than the threshold value would be beneficial for the project because such an item would impose additional operational costs: up to about $3,845 for a score of 68 %.

This type of analysis is essential for enabling a contractor to predict the range of acceptable U-values for windows under submission and to assess the amount of compensation he or she is willing to negotiate and cover. A submittal for a window with a U-value of 1.60 $W/m^2.^{\circ}K$, for example, would achieve a high performance-level score (86 %), but the contractor would have to agree to provide compensation of approximately $1,900 in order for this item to be approved. If the contractor can manage to offer a better U-value option that is less than 1.60 $W/m^2.^{\circ}K$, e.g., 1.55 $W/m^2.^{\circ}K$, the amount of compensation would be reduced to about $1,500: a 21 % difference. The amount saved in compensation also represents a direct advantage with respect to overall project performance because the long-term operational implication is not as great.

6.4 Multiple-Parameter Sensitivity Analysis

Achieving a score above the threshold (80 %) is not always associated with submitting only a superior U-value and neglecting the other criteria. A high score can also be achieved through multiple combinations of all parameters. Thus, a multiple-parameter sensitivity analysis has also been incorporated as a means of examining changes in the submittal score as a function of changes in all window parameters. The Monte Carlo simulation incorporated 5,000 scenarios with random variations in the parameters. Five thousand scenarios provided a sufficient representation of the variability in the range of window options because testing with a greater number of scenarios had no effect on the overall pattern of the results. Based on the results of the 5,000 scenarios, a probability distribution for the evaluation score was created and analyzed, followed by an analysis of the compensation amounts. For the case study, the two borderline options (Option 1 and Option 3) were analyzed, as explained below.

Window Option 1: The Monte Carlo simulation was carried out for 5,000 scenarios related to window Option 1. To introduce practical scenarios into the sensitivity analysis, random variations were limited to practical ranges of variations in the parameters. For window Option 1, it was assumed that the fabricator produces windows with U-values that vary only within +5 % from the submitted value, as shown in Table 6-2. The chance of lower ratings for air infiltration and water penetration is 30 %, and the probability that they will remain unchanged is 70 %. The VT and SHGC are assumed to vary within a range of ±20 % of the initial value. Based on these conditions, 5,000 randomly created scenarios were evaluated using the developed system, and their evaluation scores were documented. Table 6-3 lists a sample of the scenarios (rows) generated using the Monte Carlo simulation. Appendix E includes additional samples of scenarios for window Option 1.

Table 6-2: Variability Ranges for Window Option 1

Criteria (parameters)	U-Value	Air Infiltration	Water Penetration	VT	SHGC
Option 1	1.6	0.55 *(A3)*	700 (*B7)*	0.85	0.5
Level of Variability	+5%	*P(A3)=* 70% *P(A2)=* 30%	*P(B7)=* 70% *P(B6)=* 30%	± 20%	± 20%

Table 6-3: Sample Scenarios for Window Option 1

Number of Scenarios	**Window Parameters**					
	U-Value	**Air Infiltration**	**Water Penetration**	**VT**	**SHGC**	**Overall Scores**
1	1.67	1.65	600	0.86	0.53	**69.65**
2	1.63	1.65	700	0.84	0.63	**73.89**
3	1.63	0.55	600	0.87	0.62	**80.93**
4	1.74	1.65	700	0.90	0.32	**64.14**
5	1.69	0.55	600	0.94	0.47	**75.87**
..	..	..	..	..	..	..
..	..	..	..	..	..	..
5000	1.60	0.55	700	0.76	0.68	**82.95**

Based on the results for the random scenarios, a normal probability distribution of the window score was developed, as shown in Figure 6-10: a mean (μ) of 78.3 and a standard deviation (σ) of 4.28. The generated distribution shows that window option 1 has a 35 % probability of meeting the 80 % acceptance threshold, even given all of the parameter variations, which is considered a good result (1,750 scenarios from a total of 5,000 scenarios). This type of analysis is essential for enabling a contractor to predict the probability that the windows being submitted will meet or surpass a specific threshold.

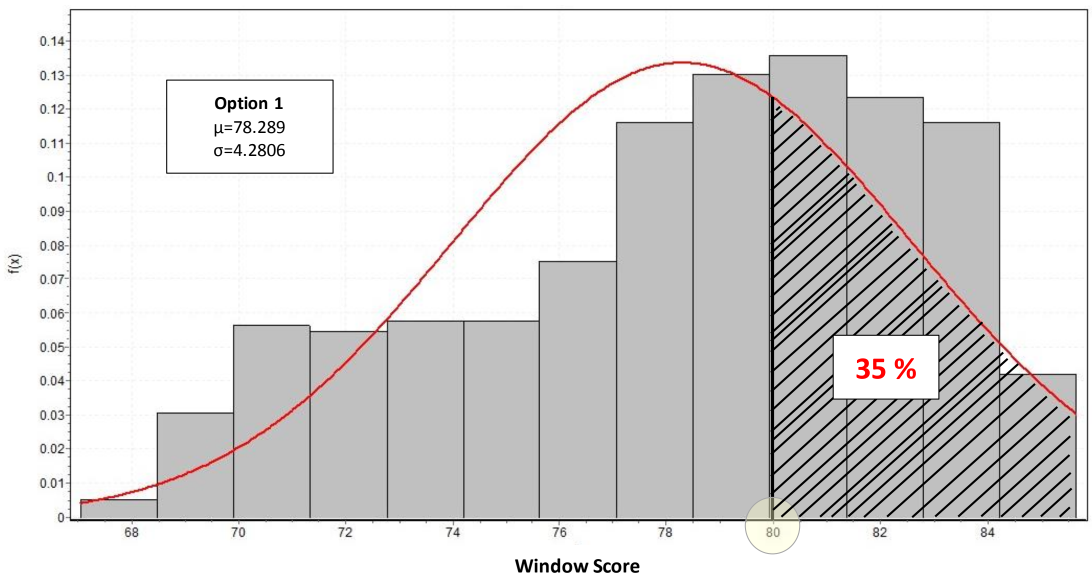


Figure 6-10: Probability Distribution Results for 5,000 Scenarios (Option 1)

To analyze the variability in compensation amount, all scenarios that met the 80 % threshold were examined further, and the range of compensation amounts was plotted, as shown in Figure 6-11. The plot shows the maximum and minimum compensation amounts (and related U-value) imposed by the set of scenarios corresponding to each evaluation score (from 80 % to 85 %). As shown in the figure, to achieve a high score (e.g., 85 %), the range of U-value is small and is limited to highest quality windows, leading to the lowest range and value of compensation.

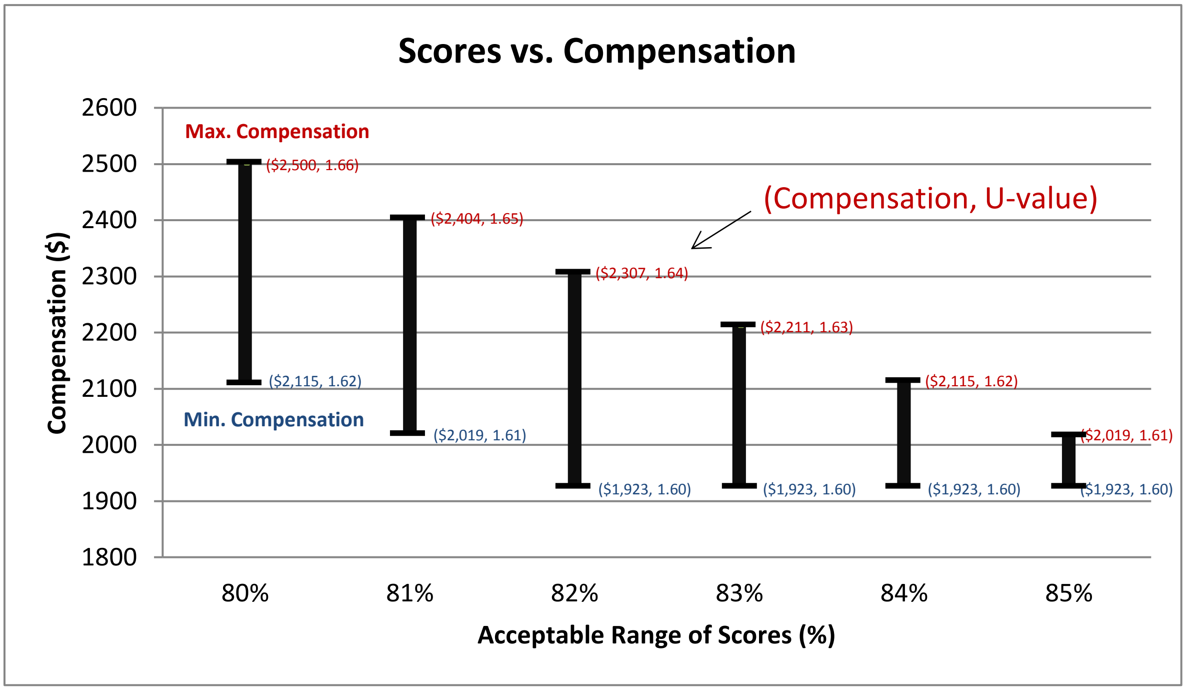


Figure 6-11: Window Option 1 Scores versus Compensation

Window Option 3: A similar analysis was performed for window Option 3. A Monte Carlo simulation was carried out for the 5,000 scenarios related to this option. To introduce the practical scenarios into the sensitivity analysis, the random variations for window Option 3 were assumed based on the fabricator producing windows with U-values that vary within +10 % from the submitted value, as shown in Table 6-4.

Table 6-4: Variability Ranges for Window Option 3

Criteria (parameters)	U-Value	Air Infiltration	Water Penetration	VT	SHGC
Option 3	1.53	1.65 *(A2)*	600 *(B6)*	0.6	0.45
Level of Variability	+ 10%	*P(A2)* or *P(A3)*= 70% *P(A1)* = 30%	*P(B6)* or *P(B7)*= 70% *P(B5)*= 30%	± 40%	± 40%

As illustrated in Table 6-4, the chance that the air infiltration and water penetration ratings will be lower is 30 %, and the probability that they will remain unchanged or be enhanced is 70 %. The VT and SHGC are also assumed to vary within a range of ±40 % from the initial value. Based on these conditions, the 5,000 randomly created scenarios were evaluated using the developed system, and their evaluation scores were documented. Appendix E includes additional samples of scenarios for window Option 3.

Based on the results for the random scenarios, a normal probability distribution for the window score was developed, as shown in Figure 6-12: a mean (μ) of 72.55 and a standard deviation (σ) of 7.24. The generated distribution shows that, given all of the parameter variations, window option 3 has only a 15 % chance (shaded area under the curve) of meeting the 80 % acceptance threshold, which is considered a relatively low probability. This percentage confirms that the contractor has narrower sets of scenarios that will adhere to the threshold if Option 3 is selected (i.e., only 750 of the total 5,000 scenarios can match or exceed the 80 % requirement).

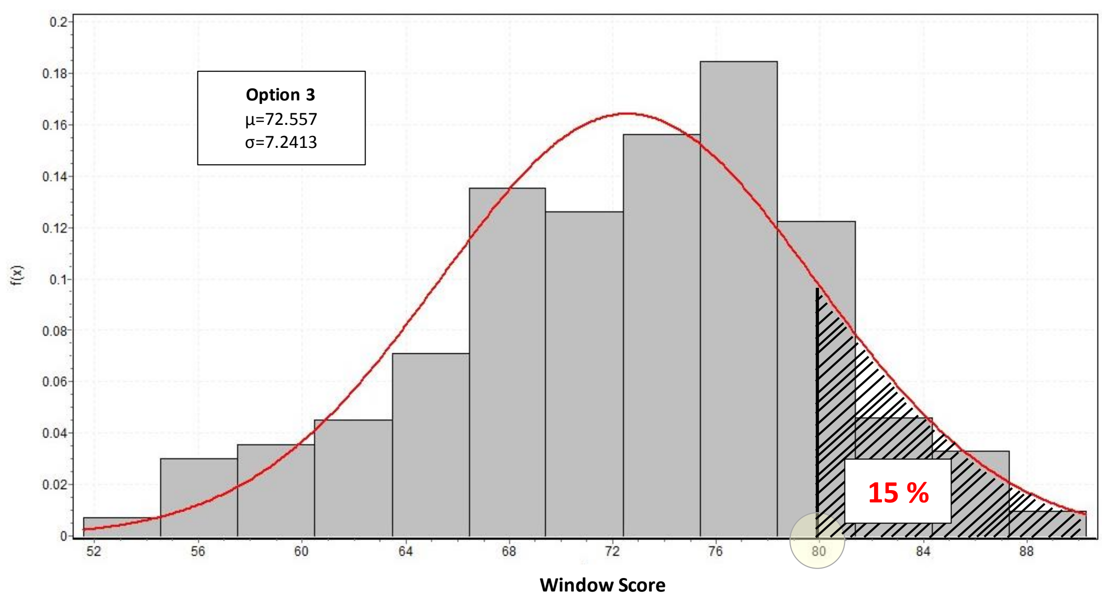


Figure 6-12: Probability Distribution Results for 5,000 Scenarios (Option 3)

To analyze the variability in the compensation amount, all scenarios that met the 80 % threshold (80 % to 89 %) were investigated further, and the ranges of compensation amounts were plotted, as shown in Figure 6-13. The plot allows the contractor to view and determine the window choices that can reduce the range of compensation amounts to an acceptable and preferred level.

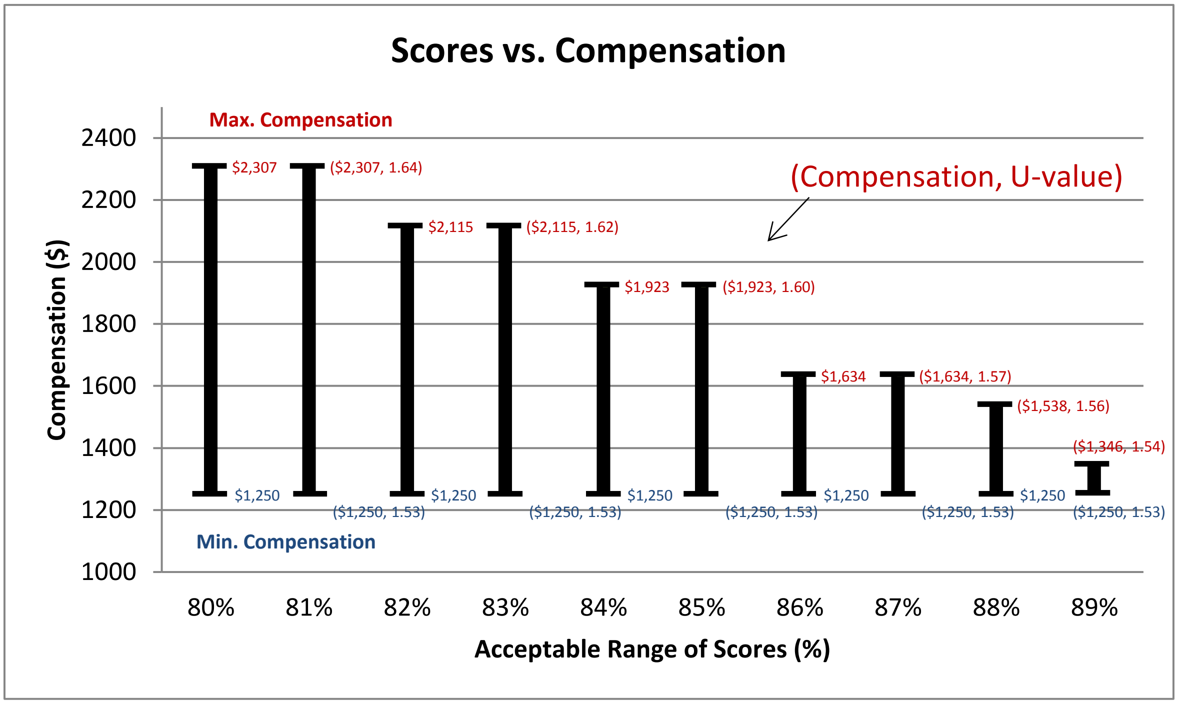


Figure 6-13: Window Option 3 Scores versus Compensation

In general, plotting the acceptable ranges of scores (80 % and above for both options) with respect to the amount of compensation revealed that the range of compensation decreases with increases in the score: the closer an option is to the threshold, the greater the range of compensation that will be imposed. Since the amount of compensation is affected only by changes in the U-value, this correlation means that, as the range of compensation becomes lower, the U-value improves. If the contractor's goal is to pay less compensation and to produce a higher score that passes the threshold with confidence, the options submitted should always entail a "better" U-value.

6.5 Conclusion

This chapter has presented a close-to-real-life case study that was tested using the prototype system. The case enabled an examination of the system when three options are submitted to a consultant with minor changes in the design rationale and performance-related criteria. The three options were checked for compliance, and one was rejected because of inconsistencies with the design rationale criteria. The two remaining options were assessed with regard to compliance with performance-related criteria and became conditionally accepted options (borderline) because they met or exceeded the predefined threshold. The borderline submittals were then reported for decision-making purposes and updated for tracking and verification purposes. A sensitivity analysis was conducted for the borderline options as a means of examining the relationship between changes in the U-value on one hand and the resulting scores and compensation amounts on the other. The analysis also helps to determine the probability that the score for a particular option will be greater than or equal to the threshold: 80 %. The evaluation process has been deemed acceptable by the consultant involved in the case study because it saves time and includes consideration of all aspects of windows. The compensation feature was of interest to the consultant because it was assessed scientifically and added value to the project. The analysis has proven that the threshold requirements can be met by several sets of combinations that suit both the contractor and the project.

Chapter 7

Conclusion

7.1 Summary and Conclusion

During construction, engineers can be overwhelmed by the submittal review process. They are always under pressure to provide speedy processing and approval of submittals in order to avoid project delays. The submittal evaluation process, however, is not simple, particularly when the submittal involves trivial deviations from the design rationale and specification requirements, which may nonetheless result in unsatisfied users and/or a negative impact on the construction/operation of the project.

Because specifications can be roughly written at the design stage, submittal evaluation can be subject to a range of interpretations, and the information needed for submittal evaluation is often scattered in different formats (textual and 2D drawings). Submittal items involving architectural components are among the most difficult to evaluate since the design rationale is often undocumented and the decision-making process is frequently hampered by a lack of defined evaluation criteria.

To investigate construction submittals, data were collected from two governmental organizations and two private A/E firms in order to identify the most critical building submittals. Complete sets of submittal logs were analyzed, and the initial analysis indicated that architectural submittals contained the greatest number of submitted items (65 % of all disciplines) and that windows were determined to be the most critical architectural submittals. All of the windows-related evaluation criteria have been listed, and the investigation of highly subjective aesthetics-related criteria has been described. The results revealed the necessity of including and specifying non-technical (subjective) criteria in the proposed submittal evaluation process.

Based on practitioner feedback, detailed window evaluation criteria were grouped into two categories: design rationale and performance-related. Design rationale criteria include all criteria described by the designer in textual and qualitative formats, whereas performance-related criteria comprise all criteria that affect building performance. The analytical hierarchy process (AHP) was then used for determining weights for the criteria, and multi-attribute utility theory (MAUT) was used for the generation of utility functions based on feedback from a number of organizations. For a submittal to be conditionally accepted, it must comply with the checklist of design rationale criteria and also satisfy a predefined acceptance threshold with respect to the performance criteria. Compliant options are then assessed, reported, and finally updated in the BIM. To provide the contractor with a mechanism for understanding what should be improved to render a submittal acceptable, a sensitivity analysis using a Monte Carlo simulation technique is also conducted as part of the developed system. The analysis enables an examination of the changes produced in the score awarded to a submittal (and also the compensation amount implicated by that submittal) as a function of modifications to the window parameters.

A prototype system of the developed framework was created with the goal of validating the working mechanism and output of the system. Revit Architecture 2011 was used as the BIM platform and was customized to incorporate all of the system functions. After development, the decision support system (DSS) prototype was tested for a number of submittal scenarios. The test scenarios were taken from the submittal logs collected, with the incorporation of a number of assumptions to compensate for missing design rationale information and specification data.

In summary, this research has demonstrated that the developed BIM-based decision support system for the evaluation of architectural submittals can be a valuable asset for construction projects, facilitating an efficient and speedy decision-making process. The new system enhances communication between project parties, results in decisions consistent with the design rationale and specification data, includes consideration of the aesthetic aspects of buildings as well as overall building performance, provides a basis for negotiation, ensures the smooth progress of construction, and increases the likelihood of the successful delivery of a project. The benefits have been validated through investigation and practitioner reviews.

7.2 Research Contributions

This research represents a number of contributions:

- **Identifying and understanding the key architectural submittals that affect building performance:** This study has investigated construction submittals and has identified key submittals based on data collected from a variety of sources. Windows were determined to be the most critical architectural items that have a significant effect on energy consumption and the overall performance of the building.
- **Documenting design rationale and performance-related criteria:** Based on an investigation of the current submittal evaluation process, an evaluation mechanism was developed for the consideration of design rationale criteria and technical criteria. The mechanism saves the reviewer time and reduces the number of evaluation loops.
- **Reducing subjectivity in the decision process:** The proposed evaluation mechanism reduces the subjectivity inherent in traditional submittal evaluation by pre-modeling the decision makers' preferences using MAUT. The use of MAUT reduces bias (personal preferences of the evaluator) in the evaluation process and facilitates speedy and automated decisions.
- **Fully utilizing BIM technology:** This research fully utilizes BIM and improves its capabilities with respect to storing evaluation criteria, including design rationale and

performance-related criteria, enhancing the submittal evaluation process, updating the as-built specifications, and facilitating improved building operation. The benefits include enhanced communication, reduction in the number of conflicts, and smoother project progress.

- **Developing a BIM-based decision support framework and a prototype system for the evaluation and approval of submittals:** The research has resulted in the development of an automated decision support system based on utility values for predefined criteria. The system offers an on-the-spot decision mechanism for reviewers and contractors. The framework contributes to speedy evaluation, fewer disputes among the parties, and the achievement of the best value for the project.
- **Integrating architectural aspects and engineering concepts**. Architectural design is based on aesthetics, function, and sustainability. The successful incorporation of these essential aspects can be achieved during construction through the utilization of engineering decision-support concepts, such as AHP, MAUT, and heat loss calculation methods.

7.3 Future Research

Potential improvements that could be incorporated into the framework developed for this thesis can be summarized as follows:

- Expand the application of the BIM-based framework to cover other architectural building components, which would enable additional evaluation since some architectural components require greater attention during the design and submittal evaluation processes, especially for monumental buildings designed as unique identifiable architectural icons.

- Integrate the framework with a comprehensive energy analysis tool that includes consideration of all building components in the heat loss calculations in order to provide a thorough assessment of operational implications.

- Link the framework to an electronic-based specification as a means of retrieving all of the BIM specifications and performing the updating step on one platform. A submittal system should also be integrated with the framework so that submittals can be officially tracked and verified.

- Use real-life 3D models for building components supplied from manufacturer databases to improve the quality of the information retrieved from the 3D BIM model.

- Enhance the use of the customized add-in button so that it functions consistently with all versions of Revit.

- Include and clearly state in the specifications the method of calculating the compensation amounts for borderline submittals.

References

1. Ababutain, A.Y. (2002). Multi-criteria decision making model for the selection of BOT toll road proposals within the public sectors. Doctoral thesis, School of Engineering, University of Pittsburgh, Pittsburgh, PA.

2. Abdel-Monem, M., and Hegazy, T. (2011). Simplified IT tools for site information tracking. *CSCE Annual Conference*, Ottawa, ON.

3. AccuBuild [Computer software]. (2014), Commercial construction software suite of products, at Theorem 44 Design Studio. *Accessed online on January 15, 2013 at http://www.accu-build.com/aboutus.php*. TX, USA.

4. AIA (2007). A201-2007 General conditions of the contract for construction. *American Institute of Architect*, AIA, 2007.

5. Aish, R. (1986). Building modeling: The key to integrated construction CAD. *CIB 5th International Symposium on the Use of Computers for Environmental Engineering Related to Buildings*, pp.356-371. From7-9 July, 1986. The Chameleon Press Limited, London.

6. Al-Hadhrami, L. M. (2013). Comprehensive review of cooling and heating degree days characteristics over Kingdom of Saudi Arabia. *Renewable and sustainable energy reviews*, 27 (November), pp. 305-314.

7. Alias, M., A., Hashim, S., Z., M., and Samsudin, S. (2009). Using fuzzy analytic hierarchy process for southern johor river ranking. *International Journal for Advanced Software Computer Applications*, 1(1), pp 62-76.

8. Ander, G., D. (2010). Windows and glazing. National Institute of Building Sciences. Accessed online June 2011 at http://www.wbdg.org/resources/windows.php.

9. Arditi, D., and Thanat, P. (2006). Selecting a delay analysis method in resolving construction claims." *International Journal of Project Management*, 24, (2), 145-155.

10. Ariosto, T., & Memari, A. M. (2013). Comparative study of energy efficiency of glazing systems for residential and commercial buildings. *AEI 2013: Building Solutions for Architectural Engineering - Proceedings of the 2013 Architectural Engineering National Conference, pp.* 408-417.

11. ASHRAE (2004a). ASHRAE standard: Air leakage performance for detached single-family residential buildings (ANSI/ASHRAE 119-1988 (RA 2004)). *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.*

12. ASHRAE (2004b). ASHRAE standard: Energy standards for buildings except low-rise residential buildings (ANSI/ASHRAE 90.1-2004). *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.*

13. ASHRAE (2009). ASHRAE Handbook - Fundamentals (SI Edition). American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Online version available at: http://app.knovel.com/hotlink/toc/id:kpASHRAE37/ashrae-handbook-fundamentals

14. Ask, A. C. (2003). Ventilation and air leakage (Research Report – 0303). *ASHRAE Journal*, November 2003. Accessed online October, 2013 from http://www.buildingscience.com/ documents /reports/rr-0303-ventilation-and-air-leakage.

15. ASTM (1999). Standard E 779-99 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization. American Society for Testing and Material (ASTM). West Conshohocken PA.

16. Atkins, J. B., and Simpson, G. A. (2006). According to hoyle: the submittals process. Journal of American Institute of Architects, AIA. Accessed online on January 15, 2009 at http://info.aia.org /aiarchitect/thisweek06/0512/0512bp_risk.cfm.

17. Attolist, L. L. C [Computer Software]. (2011). Submittal Software, *Accessed online on March 10, 2011 http://www.newformaprojectcloud.com/submittal-software*.

18. Autodesk (2010). Autodesk navisworks products. Autodesk white Paper. *Accessed online on March 10, 2010 at* http://usa.autodesk.com/navisworks/features/.

19. Autodesk (2011). Realizing the benefits of BIM. Autodesk white Paper. *Accessed online on January 15, 2011 at* www.autodesk.com/bim.

20. Azhar, S. (2011). Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. *Leadership Management Engineering*, 11(3), pp. 241–252.

21. Bahaj, A. S., James, P. A. B., and Jentsch, M. F. (2008). Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. *Energy and Buildings, 40*(5), pp. 720-731.

22. Baker, P. (2012). Measure guideline: Wood window repair, rehabilitation, and replacement (U. S. Department of Energy Building America Report - 1203). *Somerville MA: Building Science Press*. Accessed online September, 2012 from http://buildingscience.com.

23. Beal, C. (1999). Thermal and moisture protection manual: for architects, engineers, and contractors. McGrawHill, New York, USA.

24. Becerik-Gerber, B., and Kensek, K. (2010). Building information modeling in architecture, engineering, and construction: emerging research directions and trends. *Journal of Professional Issues in Engineering Education and Practice*, 136(3), pp 139-147.

25. Belton, V., and Stewart, T. J. (2002). Multiple criteria decision analysis: an integrated approach. Kluwer Academic Publisher Group, Springer USA.

26. Birx, G. W. (2005). BIM evokes revolutionary changes to architecture practice at ayers/saint/gross. *Journal of American Institute of Architects, AIA. Accessed online on March 10, 2009 at* http://info.aia.org/aiarchitect/thisweek05/tw1209/tw1209changeisnow.cfm.

27. Bliss, S. (2006). Best practices guide to residential construction: materials, finishes, and details. Hoboken, New Jersey, USA.

28. Blomsterberg, Ake K., and David T. Harrje. (1979). Approaches to evaluation of air infiltration energy losses in buildings. ASHRAE Journal (85), Part 1, pp. 797-815.

29. Bozdoc, M. (2003). CAD Chronology: the 80's. *Accessed online on April 09, 2010 at* http://mbinfo.mbdesign.net/CAD1980.htm.

30. BuildSite [Computer Software]. (2009). BuildSite Software for Electronic Submittals. Automate the submittal process. *Accessed online on October 09, 2010 at* http://buildsite.com/info/products/submittals/, California, USA

31. Bulow-Hube, H. (2001). Energy-efficient window systems: effects on energy use and daylight in building. Doctoral thesis, Division of Energy and Building Design, Department of Construction and Architecture, Lund University, Sweden.

32. Bunzick, J. P. (2007). Getting submittals under submission. *The Construction Specifier*, *60*(12), 20.

33. Carmody, J., Selkowitz, S., Arasteh, D., Lee, E. S., and Willmert, T. (2004). Window systems for high-performance buildings (1st ed.). W W Norton & Co Inc , New York , USA.

34. Carrick, A. (2011). New construction in Canada will reach $300 billion by 2014. *Journal of Commerce.* Burnaby: Reed Construction Data. Accessed online May 2012 from http://www.journalof commerce.com/article/id43799.

35. CGSB (1986). CAN/CGSB-149.10-M86, Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method. Canadian General Standards Board (CGSB).

36. CI (2007). Are specifications not important anymore? *Official site of the Construction Institute CI Newsletter, ASCE, 7(1)*, http://www.cizone.org/jan_feb_07/ specifications.html.

37. CIBSE. (2006) Degree-days: theory and application (TM41: 2006). *The Chartered Institution of Building Services Engineers (CIBSE), London, England*. Accessed online September, 2013 from cibse.org.

38. CMHC (2003). Water penetration resistance of windows - Study of codes, standards, testing, and certification. *Research Highlights, Technical Series 03-125, November 2003*. Canada Mortgage and Housing Corp (CMHC), Ontario, CA. Accessed online January 2014 from http://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/03-125-e.htm

39. CMHC (2008). Assessment of natural ventilation for Canadian residential buildings. *Research Highlight, Technical Series 08-100, February 2008*. Canada Mortgage and Housing Corp (CMHC), Ontario, CA. Accessed online January 2014 from http://publications.gc.ca/collections/collection_2008/cmhc-schl/nh18-22/NH18-22-108-100E.pdf

40. Colliver, D. G. (2000). A predictive method to determine the leakage area needed in residences for IAQ control by infiltration. Dublin 2000: 2020 Vision, Chartered Institution of Building Services Engineers (CIBSE).

41. Construction Communicator [Computer Software] (2009). *Accessed online on October 09, 2010 at* http://www.constructioncommunicator.com/features-and-benefits.html.

42. CSA (2006). User selection guide to CSA Standard CAN/CSA-A440-00: Windows (A440.1-00). *Canadian Standards Association, Mississauga, CA*. Accessed online January 2011 from http://ccinfoweb2.ccohs.ca/legislation/documents/stds/csa/cusgc00e.htm

43. CSA (2009). User guide to CAN/CSA-A440.2-09: Fenestration energy performance (A440.3-09). *Canadian Standards Association, Mississauga, CA*. Accessed online January 2011 from http://ccinfoweb2.ccohs.ca/legislation/documents/stds/csa/a440309e.htm

44. CSBR. (2007). Window materials & assemblies: glazing materials. *Center for Sustainable Building Research (*CSBR), University of Minnesota, USA.

45. de la Garza, J., and Alcantara, P. Jr. (1997). Using parameter dependency network to represent design rationale." *Journal of Computing in Civil Engineering*, 11(2), pp. 102-112.

46. de la Garza, J., and Oralkan, G. (1992). An object space framework for design/construction integration. *Building and Environment. International Journal of Building Science and Its Applications*, 27(2), pp. 243-255.

47. de LAPP, J. A., (2003). Impacts of CAD on submittal process. Master of Science Thesis, Texas A&M University, USA.

48. Demchak, G., Dzambazova, T., and Krygiel, E. (2009). *Introducing revit architecture 2009: BIM for beginners*. Sybex, USA.

49. Duran, O. (2011). Computer-aided maintenance management systems selection based on a fuzzy AHP approach. *Advances in Engineering Software*, 42(10), pp. 821-829.

50. East, E. W. (2007). Construction operations building information exchange (COBIE): requirements definition and pilot implementation standard. Construction Engineering Research Laboratory, US Army Corps of Engineers, Engineer Research and Development Center, Champaign, IL, USA.

51. Eastman, C. M. (1975). The use of computer instead of drawings in building design. *Journal of American Institute of Architects March 1975*, pp. 46-50.

52. Eastman, C. M. (1992). Modeling of buildings: evolution and concepts. *Automation in Construction*, 1(2), pp. 99-109.

53. Eastman, C. M. (1999). Building product models: computer environments, supporting design and construction. CRC Press LLC. Florida, USA.

54. Eastman, C., (2009). What is BIM? Digital Building Lab, Georgia Tech. Accessed online on February 2010 at http://bim.arch.gatech.edu/?id=402.

55. Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors, 2nd edition. John Wiley & Sons, Inc., USA.

56. Elovitz, K. M. (2002). Shop drawing review: what does the contract say?. *Consulting-Specifying Engineer*, 32(6),13.

57. Elovitz, K. M. (2003). A Guide to shop drawings: who should review?. *Consulting-Specifying Engineer*, Reed Elsevier Inc., USA.

58. Emmitt, S. (2001). Observing the act of specification. *Design Studies*, 22(5), pp. 397-408.

59. Fennell, H. C., & Haehnel, J. (2005). Setting airtightness standards. *ASHRAE Journal, 47 (9), September 2005*, pp. 26-30.

60. French, S. (1988). Decision theory: an introduction to the mathematics of rationality. Ellis Horwood, Chichester, UK.

61. Friedlander, M. C. (2000). Shop drawing 'approval' liability. *Consulting-Specifying Engineer* 28(5), 21.

62. Furman, G., Hochstatter, J., Jones, G., and Oxendine, F. (2005). System and method for generating construction document submittal packages. Available online at http://www.freepatentsonline.com/y2005/0188299.html.

63. Gallaher, M. P., O'connor, A. C., Dettbarn, J. L., and Gilday, L. T. (2004). Cost analysis of inadequate interoperability in the U.S. capital facilities industry. *The National Institute of Standards and Technology (NIST)*, NIST GCR - 04-867.

64. Ganeshan, R., Garrett, J., and Finger, S. (1994). A Framework for representing design intent. *Design Studies*, 15(1), pp. 59-84.

65. Garden, G. K. (1964). Glazing design. *Canadian Building Digests (55)*. National Research Council Canada, Ottawa, CA. Available online at archives, http://archive.nrc-cnrc.gc.ca/eng/ibp/irc/cbd/building-digest-55.html.

66. Garrett, D. F. and Lee, J. (2010). Lean construction submittal process - a case study. *Quality Engineering 23(1)*, pp. 84-93.

67. Gelder, J. (2007). Specifications: problems in practice. National Building Specification, United Kingdom.

68. Goedert, J. D., and Meadati, P. (2008). Integrating construction process documentation into building information modeling. *Journal of Construction Engineering and Management*, 134(7), pp. 509-516.

69. Golden, B., Wasil, E., and Harker, P. (1989). The analytic hierarchy process: applications and studies. Springer Berlin Heidelberg, NY, USA.

70. Goncalves, M. D., Jutras, R., and Velji, M. (2007). Evaluating the field performance of windows and curtain walls of large buildings. *2007 Symposium on Building Envelope Technology, Boston*, November 2007.

71. Goodwin, P., and Wright, G. (1998). Decision analysis for management judgment, 2nd edition. John Wiley & Sons, Inc., Chichester, England.

72. Grynning, S., Gustavsen, A., Time, B., and Jelle, B. P. (2013). Windows in the building of tomorrow: energy losers or energy gainers?, *Energy and Buildings*, 61(2013), pp. 185-192.

73. Gunterman, A. (1982). A simplified degree-day method for commercial and industrial buildings. *ASHRAE Journal (24), pp. 29-32.*

74. Halter, A.N., and Dean, G. W. (1971). Decision under uncertainty with research applications, South-Western Publishing, Cincinnati, USA.

75. Hardin, B. (2009). BIM and construction management: proven tools, methods, and workflows, Sybex Publisher, USA.

76. Harris, E. (2006). Construction project submittal management. Accessed online on September 2009 at http://www.freepatentsonline.com/7062514.html.

77. Hegazy, T, Zeneldin, E, and Grierson, D. (2001). Improving design coordination for building projects. I: information model. *Journal of Construction Engineering and Management*, 127(4), pp. 322-329.

78. Hegazy, T. (2002). Computer-based construction project managemen. Pearson Education, New Jersey, USA.

79. Hinze, J. (2010). Construction contracts, 3rd Edition. McGraw Hill, New York, USA.

80. Hipel, K.W. (1992). Multiple objective decisions making in water resources. *JAWRA Journal of the American Water Resources Association* 28(1), pp. 3-12.

81. Hipel, K.W., and Ben-Haim, Y. (1999). Decision making in uncertain world: information-gap modeling in water resources management. *IEEE Transactions on System, Man, and Cybernetics*, 29(4), pp. 506-517.

82. Hipel, K.W., Radford, K. J., and Fang, L. (1993). Multiple participant multiple criteria decision making. *IEEE Transactions on Systems, Man, and Cybernetics, SMC* 23(4), pp.1184-1189.

83. Ho, W., (2008). Integrated analytic hierarchy process and its applications - A literature review. *European Journal of Operational Research*, 186(1), pp. 211-228.

84. Hobbs, B. F., and Meier, P. (2000). Energy Decisions and the Environment: A Guide to the Use of Multicriteria Method. Kluwer Academic Publishers, Boston, 2000.

85. Holness, G. V. R. (2006). Future direction of the design and construction industry building information. *ASHRAE Journal*, 48(8), pp. 38-44.

86. Horvat, M. (2005). Protocol and assessment tool for performance evaluation of light frame building envelopes used in the residential building. Doctoral thesis, Concordia University, Montreal, Quebec, Canada

87. Huang, J. and Franconi, E. (1999). Commercial Heating and Cooling Loads Component Load Analysis. *Building Technologies Department, Lawrence Berkeley National Laboratory: LBNL-37208*, Berkeley, CA

88. Ingold, D. (2010). Is Construction Submittal Process Really That Important?. Accessed online on July 2011 at http://buildipedia.com/aec-pros/from-the-job-site/is-the-construction-submittal-process-really-that-important

89. InterSpec (2007). Link your drawings with specifications with e-SPECS. Accessed online July 2007 at http://www.e-specs.com/.

90. Iskidag, U., and Underwood, J. (2010). Two design patterns for facilitating building information model-based synchronous collaboration. *Automation in Construction* 19(5), pp. 544-553.

91. Iyer, G. R., Mills, J. J., Barber, S., Devarajan, V., and Maitra, S. (2006). Using a context-based inference approach to capture design intent from legacy CAD. *Computer-Aided Design & Applications*, 3(1–4), pp. 269-278.

92. Jahren, C. T. and Dammeier, B. F. (1990). Investigation into construction disputes. *Journal of Management in Engineering, ASCE*, 6(1), pp. 39-46.

93. Jin, Y. and Ishino, Y. (2006). Daka: Design activity knowledge acquisition through data-mining. *International Journal of Production Research*, 44(14), pp. 2813-2837.

94. Josephson, P. E. and Hammarlund, Y. (1999). The causes and costs of defects in construction: a Study of seven building projects. *Automation in Construction*, 8(6), pp. 681-687.

95. Khemlani, L. (2005). CORENET e-PlanCheck: singapore's automated code checking system. AECbytes, Accessed online April 2009 at http://www.aecbytes.com/buildingthefuture/2005/CORENETePlanCheck.html.

96. Khemlani, L. (2008). Autodesk navisWorks 2009. AECbytes Product Review, Accessed online on August 2010 at http://www.aecbytes.com/review/2008/NavisWorks2009.html.

97. Khemlani, L. (2009a). Collaboration, project management, and project information management solutions in AEC. Accessed online on July 2010 at http://www.aecbytes.com/feature/2009/Collaboration_PM_PIM_Solutions.html.

98. Khemlani, L. (2009b). Solibri model checker. AECbytes Product Review. Accessed online on July 2010 at http://www.aecbytes.com/review/2009/SolibriModelChecker.html.

99. Khemlani, L. (2010). Tekla structures 16. AECbytes Product Review. Accessed online on August 2011 at http://www.aecbytes.com/review/2010/TeklaStructures16.html.

100. Khemlani, L. (2011a). Revit Architecture 2012. AECbytes Product Review. Accessed online on August 2011 http://www.aecbytes.com/review/2011/RevitArch2012.html.

101. Khemlani, L. (2011b). ArchiCAD 15. AECbytes Product Review. Accessed online on August 2011 at http://www.aecbytes.com/review/2011/ArchiCAD15.html.

102. Khemlani, L. (2011c). Vectorworks architect 2011. AECbytes Product Review. Accessed online on August 2011 at http://www.aecbytes.com/review/2011/VectorworksArchitect2011.html.

103. Khemlani, L. (2011d). Newforma project center eighth edition. AECbytes Product Review. Accessed online on August 2011 at http://www.aecbytes.com/review/2011/NewformaProjectCenter8.html.

104. Khouw, N. (2012). Gender differences: The meaning of color for gender. *The Color Matters eBook*. Accessed online May 2013 from http://www.colormatters.com/color-symbolism/gender-differences.

105. Kilgour, D. M. (2007). Diplomacy game: the graph model for conflict resolution as a tool for negotiators. Part IV, pp. 251-263, Springer Berlin Heidelberg.

106. Kilper, C. W. (2002). Are construction submittals irrelevant?, *Consulting-Specifying Engineer, Reed Elsevier Inc.* Accessed online July 2012 at http://www.csemag.com/industry-news/codes-and-standards-updates/single-article/are-construction-submittals-irrelevant/1de56292ce.html

107. Kronvall, Johnny. (1978). Testing of Houses for Air Leakage Using a Pressure Method. *ASHRAE Journal (84), Part 1, pg 72-79.*

108. Kululanga, G. K. and Price, A. D. (2005). Measuring quality of writing of construction specifications. *Journal of Construction Engineering and Management*, 131(8), pp. 859-865.

109. Laiserin, J. (2002). Comparing pommes and naranjas. *The LaiserinLetter (*15). Available online at http://www.laiserin.com/features/issue15/feature01.php.

110. Lee, G., Sacks, R., and Eastman, C. (2006). Specifying parametric building object behavior (BOB) for a building information modeling system. *Automation in Construction*, 15(6), pp. 758-776.

111. Liescheidt, S. (2003). Getting what you specify, part three: from lawyers to last minutes changes, plenty of potential hurdles remain in the home stretch of a project. *Engineered System*, Business News Publishing Co. Available online at http://www.highbeam.com/doc/1G1-109664895.html

112. Lindal, P. J., and Hartig, T. (2013). Architectural variation, building height, and the restorative quality of urban residential streetscapes. *Journal of Environmental Psychology, 33 (2013)*, pp. 26-36. Philadephia: Elsevier.

113. Lstiburek, J. and Carmody, J. (1993). Moisture control handbook: Principles and practices for residential and small commercial buildings. Van Nostrand Reinhold, New York, USA.

114. MasterFormat (2004). CSI, Construction Specifications Institute and CSC, Construction Specifications Canada. MasterFormat 2004 Edition Numbers & Titles 2004.

115. Matsumoto, I, T., Stapleton, J., Glass, J., and Thorpe, T. (2005) A knowledge-capture report for multidisciplinary design environments. *Journal of Knowledge Management*, 9(3), pp. 83-92.

116. McGreevy, S. L. (2002). What constitutes a designer's approval?. Accessed online on July 2009 at http://contractormag.com/law/cm_column_15/.

117. Mead, S. P. (2001). Developing benchmarks for construction information flows. *Journal of Construction Education*, 6(3), pp. 155-166.

118. Mincks W. R. and Johnston, H. (1998). Construction jobsite management. Delmar Publishing, Albany, NY, USA.

119. Moore, J. H., and Weatherford, L. R. (2001). Decision modeling with microsoft excel, 6thEdition. Prentice Hall, New Jersey, USA.

120. Morgan, M. R. P. (1995). Color me blue … or red or green? Lessons from the literature on color and usability. *Professional Communication Conference, 1995. IPCC '95 Proceedings. Smooth sailing to the Future. IEEE International*, pp.72-75. From 27-29 Sept. 1995, Savannah, GA.

121. Musser, W. N., Wetzstein, M. E., Reece, S. Y., Musser, L. M., Varca, P. E., and Chou, C. C. J. (1994). Classification of risk preferences with elicited utility data: Does the functional form matter?. *Agricultural Economics Journal* (9), pp. 322-328.

122. NASA (2009). SpecsIntact: An automated system for preparing standardized facility construction specifications. Accessed online on September 2009 at http://specsintact.ksc.nasa.gov/.

123. National BIM Standard (NBIMS). (2007). Version 1-Part 1: Overview, principles, and methodologies. National Institute of Building Science. USA.

124. NAVFAC (2006). Unified facilities guide specifications (UFGS) format standard: Unified Facilities Criteria (UFC) 1-300-2. National Institute of Building Science. USA.

125. NEB (2012). Canadian energy overview 2011 (Energy briefing note). National Energy Board (NEB). Accessed online August, 2012 from http://www.neb-one.gc.ca/clfnsi/rnrgynfmtn/nrgyrprt/nrgyvrvw/cndnnrgyvrvw 2011/cndnnrgyvrvw2011-eng.pdf.

126. Newforma (2011) [Computer Software]. Newforma project centre. Accssed online August 2011 at http://www.newforma.com/Project-Center/Solution.aspx.

127. NFRC (2013). Procedure for determining fenestration product u-factors (NFRC 100 – 2010 E1A8). *National Fenestration Rating Council*, Greenbelt, MD

128. NRCAN (2011a). Comprehensive energy use database tables. Ottawa: Office of Energy Efficiency, Natural Resources Canada (NRCAN). Accessed online September, 2013 from http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/comprehensive_tables/list.cfm?attr=0.

129. NRCAN (2011b). Energy-efficient residential windows, doors and skylights: Updated October 2010 [Pdf file]. Ottawa: Office of Energy Efficiency, Natural Resources Canada (NRCAN). Accessed online September, 2013 from http://www.nrcan.gc.ca/sites/oee.nrcan.gc.ca/files /files/pdf/equipment/ windows-door-skylights-e-web-version.pdf.

130. Olson, E., K., O'Keefe, E., W., and Jeffrey, A., E. (2009). Windows and leak-free performance: Monitoring quality from pre-construction to beyond. *The Construction Specifier*, November issue, pp. 78-85.

131. Ostanik, M. (2007). Construction submittal and shop drawing liability. Textura Corporation,USA. Accsessed online on July 2010 at http://www.submittalexchange.com/ public/pdf/Construction%20Submittal%20and%20Shop%20Drawing%20Liability.pdf.

132. Pan, N.-F. (2009). Fuzzy AHP approach for selecting the suitable bridge construction method. *Automation in Construction, Elsevier*, 17(8). Pp. 958-965.

133. Pedersen, C. & Hellevang, K. (2010). Determining insulation and air infiltration levels using an infrared thermometer - AE-1373 *Revised. North Dakota State University, Fargo, ND.* Accessed online September 2013 from http://www.ag.ndsu.edu/pubs/ageng/structu/ae1373.pdf

134. Piccolo, R. A. (2007). The secret to moving plans through the review process-Be complete. *Control Engineering*. Accessed online on September 2010 at http://www.controleng.com/single-article/the-secret-to-moving-plans-through-the-review-process-be_complete/b03bd8dfff6dccf627 e35fcc6efbdcad.html

135. Poles, M.,S. (1995). Construction defects can be avoided!. MPGroup - Construction Consultants, West Hollywood, CA. Available online at http://www.mpgroup.com/documents/Construction-Defects-Can-Be-Avoided.pdf.

136. Porter, J. E (2009). Submittal administration. *American Institute of Architects (AIA)*. Accessed online on July 2009 at http://aia.org/akr/Resources/Documents/AIAB079691?dvid=& recspec=AIAB079691.

137. RDH (2002). Water penetration resistance of windows – Study of manufacturing, building design, installation and maintenance factors. *RDH Building Engineering Limited, Vancouver, BC, Canada*.

138. RDH (2013). Review of window energy rating procedure in Canada: Final research report (January 2013). *RDH Building Engineering Limited, Vancouver, BC, Canada*.

139. Rice, T., and Haug, A. (2007). Managing submittals at LMN architects: Before Newforma project center and after. AECbytes Product Review. Accessed online on July 2009 at http://www.aecbytes.com/feature/2007/ManagingSubmittals.html.

140. Roberson, J. (2004). Effect of Building Airtightness and Fan Size on the Performance of Mechanical Ventilation Systems in New U.S. Houses: A Critique of ASHRAE Standard 62.2-2003. *Master of Science in Architecture Thesis*, University of California, Berkeley, Berkeley, CA.

141. Rockey, B. M. (2005). Electronic submittal method and system. Accessed online on July 2009 at http://www.freepatentsonline.com/y2005/0108232.html.

142. Rosen, H. J., Kalin, M., Weygant, R. S., and Regener, J. R. Jr. (2010). Construction specifications writing: Principles and procedures, 6th Edition. John Wiley & Sons, Inc., New Jersey, USA.

143. Roy, B. and Vanderpooten, D. (1996). The European school of MCDA: Emergence, basic features and current works. *Journal of Multi Criteria Decision Analysis*, 5(1), pp. 22-37.

144. Saaty, T. L. (1980). The analytical hierarchy process. John Wiley & Sons, Inc., NY, USA.

145. Saaty, T. L. (1990). How to make a decision: the analytic hierarchy process. *European Journal of Operational Research*. (48), pp. 9-26.

146. Saaty, T. L. (2001). Decision-making with dependence and feedback: The analytic network process, 2nd edition. RWS Publications, Pittsburgh, PA, USA.

147. Sabol, L. (2007). Technology, change, and the building industry. *Real State Review* 36(3).

148. Sadineneni, S. B., Madala, S. and Boehm, R. F. (2011). Passive building energy savings: a review of building envelope components. *Renewable and Sustainable Energy Reviews, 15(2011),* pp. 3617-3631

149. Sartori, I. (2008). Modeling energy demand in the Norwegian building stock-issues related to case studies and scenario analysis. Doctoral thesis, Norwegian University of Science and Technology, Trondheim, Norway.

150. Schinnerer, V. O. (2003). The Value of Establishing Submittal Procedures. Accessed online on July 2009 at http://www.schinnerer.com/risk-mgmt/Pages/Contractors.aspx.

151. Seletsky, P. (2004). Goodbye CAD. goodbye BIM. hello PEN. AECbytes Product Review, Accessed online on July 2009 at http://www.aecbytes.com/viewpoint/2004/issue_3.html.

152. Sherbini, K. (2010). Decision support system for value-based evaluation and conditional approval of construction submittalsDoctoral thesis, University of Waterloo, Ontario, Canada.

153. Sherman, M. (2009). Infiltration in ASHRAE's residential ventilation standards (LO-09-085). *ASHRAE Journal, 115(2), pp. 887-896*.

154. Shim, J. P. (1989). Bibliographical research on the analytic hierarchy process (AHP). *Socio-Economic Planning Sciences*, 23(3), pp. 161-167.

155. Shipman, F. M. and McCall, R. J. (1997). Integrating different perspectives on design rationale: Supporting the emergence of design rationale from design communication. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing,* 11 (2), pp. 141-154.

156. Silver, E. S. (2005). GSA to require building information models by FY 2006. Accessed online on July 2009 at http://enr.construction.com/news/informationtech/archives/050121.asp.

157. Simpson, G. A., and Atkins, J. B. (2005). Master and commander, part II: The architect's shared authority. *Journal of American Institute of Architects, AIA,* Accessed online on July 2009 at http://info.aia.org/aiarchitect/thisweek05/tw1111/tw1111bp_riskmgmt.cfm.

158. Sing, T. F. and Zhong, Q. (2001). Construction and real estate NETwork (CORENET). Accessed online on July 2010 at http://www.rst.nus.edu.sg/staff/singtienfoo/facilities%20Vol%2019-11&12.pdf.

159. Smith, D. K., and Edgar, A. (2008). Building information modeling (BIM). National Institute of Building Sciences, Washington, DC, USA. Accessed online on July 2010 at http://www.wbdg.org/bim/bim.php.

160. Stamps, A. E., III. (1999). Physical determinants of preference for residential facades. *Environment and Behavior, 31(6),* pp 723-751. Thousand Oaks CA: Sage Publications, Inc.

161. Stephens, B. (2013). Window and storefront thermal performance. *The Construction Specifier*, November issue, pp. 16-28.

162. Straube, J. (2006). The building enclosure. Building Science Digest, Accessed online September 2012 from http://www.buildingscience.com/documents/digests/bsd-018-the-building-enclosure_revised/?searchterm=building%20envelope.

163. Straube, J. (2010). The future of window technology is here. *Journal of Building Enclosure Design*, *Winter 2010 Issue*, pp 13-15.

164. Stutzman, D. A. (2012). Storefronts, curtain walls, windows, window walls. *The Construction Specifier*, July issue, pp. 56-63.

165. Sung, R., Ritchie, J. M., Rea, H. J., and Corney, J. (2011). Automated design knowledge capture and representation in single-user CAD environment. *Journal of Engineering Design*, 22(7), pp. 487-503.

166. Tan, X., Hammad, A., and Fazio, P. (2007). Automated code compliance checking of building envelope performance. Technical Council on Computing and Information Technology of the ASCE, Pittsburgh, Pennsylvania, USA.

167. Tavakoli, A. (1990). SUBMIT: An automated submittal management system. *Cost Engineering*, 32(6), pp. 33-5.

168. Toole, T. M., and Hallowell, M. (2005). Building performance engineering during construction. American Society of Civil Engineers, Reston, VA, United States.

169. Turkaslan-Bulbul, M., Akin, O. (2006). Computational support for building evaluation: Embedded Commissioning Model. *Automation in Construction*, 15(4), pp. 438-447.

170. Turner, W. J. N., Sherman, M. H., & Walker, I. S. (2012). Infiltration as ventilation: Weather-induced dilution. *HVAC&R Research*, 18(6), pp. 1122-1135.

171. U.S. Department of Energy (2010). Annual energy outlook 2010 with projections to 2035. Washington DC: Energy Information Administration, U.S. Department of Energy. Accessed online September 2012 from http://www.eia.gov/oiaf/archive/aeo10/pdf/0383%282010%29.pdf.

172. U.S. Department of Energy (2011). Building Technologies Program: Air leakage guide. Washington DC: Energy Efficiency & Renewable Energy, Building Energy Codes, U.S. Department of Energy.

173. U.S. Department of Energy (DOE). (2012). Annual energy review 2011. Washington DC: Energy Information Administration, U.S. Department of Energy. Accessed online September 2012 from http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf.

174. Union Gas. (2010). Wise energy guide: Conserve · save · comfort. Accessed online July, 2013 from http://www.uniongas.com/~/media/residential/energyconservation/education/wiseEnergyGuide/WEG_Booklet_Web_Final.pdf.

175. UNEP (2007). Buildings and climate change: Status, challenges and opportunities. United Nations Environment Programme (UNEP). Available online at http://www.unep.fr/shared/publications/pdf/ DTIx0916xPA-BuildingsClimate.pdf.

176. Van Naderveen, G. A. and Tolman, F. P. (1992). Modeling multiple views on buildings. *Automation in Construction*, 1(3), pp. 215-224.

177. Varshney, K., Rosa, J. E., & Shapiro, I. (2012). Method to diagnose window failures and measure U-factors on site. *International Journal of Green Energy*, 9(3), pp. 280-296.

178. Varshney, K., Rosa, J. E., Shapiro, I., & Scott, D. (2013). Air-infiltration measurements in buildings using sound transmission loss through small apertures. *International Journal of Green Energy*, 10(5), pp. 482-493.

179. Vartanian, O., Navarrete, G., Chatterjee, A., Fich, L. B., Leder, H., Modroño, C., Nadal, M., Rostrup, N., and Skov, M. (2013). Impact of contour on aesthetic judgments and approach-avoidance decisions in architecture. *Proceedings of the National Academy of Sciences (PNAS) 2013, 110 (2),* pp. 10446-10453.

180. Vico [Computer Software] (2010). VICO Software-integrating construction. VICO Inc., Colorado, USA. Accessed online on July 2010 at http://www.vicosoftware.com/.

181. Wilbur, B. M. (2009). Electronic information in formation. *The Construction Specifier*, September issue, pp. 54-63.

182. Williams, O. (1997). Contractor submittal procedures. Department of the Army - U.S. Army Corps of Engineers. Washington, DC. USA.

183. Wood, W. A. (1996). Preparing construction submittals. *Military Engineer*, 88(581), pp. 51-52.

184. Wyatt, D. J. (1997). The submittal process. *The Construction Specifier*, July issue.

185. Wyatt, D. J. (2006). What submittals tell us. *The Construction Specifier*, 59(5), pp. 26-28.

186. Yang, Z., Liu, B., and Zhao, H. (2004). Energy saving in building construction in China: A review. *International Journal of Green Energy*, 1(2), pp. 209–25.

187. Young Jr., N. W., Jones, S. A., Bernstein, H. M., and Gudgel, J. E. (2009). The business value of BIM: Getting building information modeling to the bottom line. SmartMarket Report, McGraw-Hill Construction.

188. Zahedi, F. (1986). The analytic hierarchy process: a survey of the method and its Applications. *Interfaces*, 16(4), pp. 96-108.

189. Zeleny, M. (1981). Multiple criteria decision making. McGraw Hill Inc, NY, USA.

190. Zeleznikow, J. (2002). Risk, negotiation and argumentation; a decision support system-based approach. *Journal of Law Probability and Risk*, 1(1), pp. 37-48.

191. Zeneldin, E, Hegazy, T., and Grierson, D. (2001). Improving design coordination for building projects. II: a collaborative system. *Journal of Construction Engineering and Management*, 127(4), pp. 330-336.

192. Zuhair, S. M. M., Taylor, D. B., and Kramer, R. A. (1992). Choice of utility function form: its effect on classification of risk preferences and the prediction of farmer decisions. *Journal of Agricultural Economics*, 6(4), pp. 333-344.

Appendix A

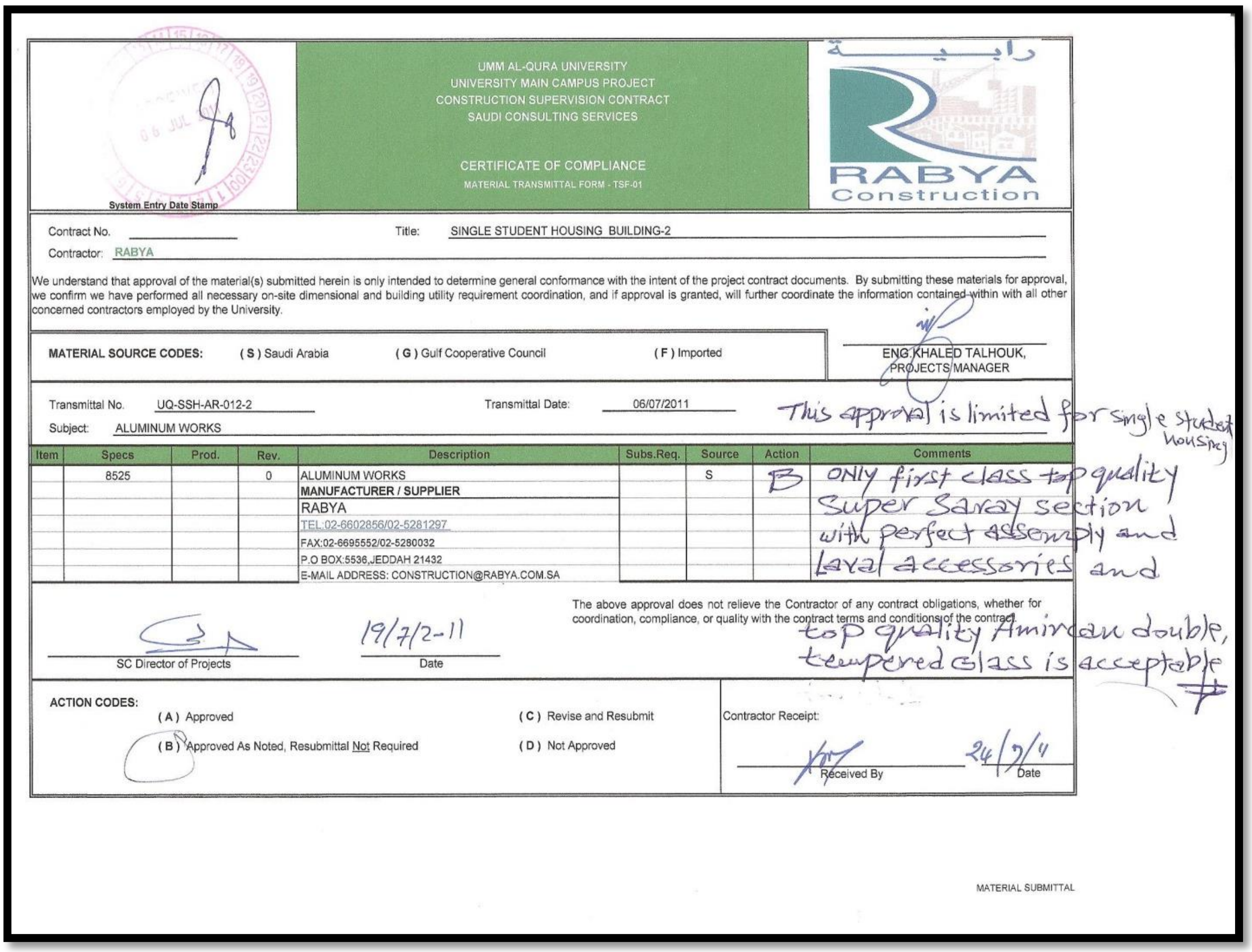
Samples of the Data Collected

PROJECT: NORTH TORONTO COLLEGIATE INSTITUTE
REF #
UPDATE: 5-Mar-12

Status Legend
R - Reviewed
NR - Not Reviewed
R+R - Revise & Resubmit
RAM - Reviewed As Modified

SECTION	ITEM	SUBMITTALS	CONTRACTOR	DATE SUBMITTED	DATE RETURNED	STATUS	SHOP DRAWING #
08520		ALUMINUM WINDOWS	STOUFFVILLE GLASS				
	01	EXTERIOR ENTRANCE FRAMING SAMPLE (3400 SERIES)		7-Nov-08	10-Dec-08	R	08520-01-00
	02	INTERIOR VESTIBULE FRAMING (Sample)		7-Nov-08	10-Dec-08	R	08520-02-00
	03	970 SERIES WINDOW SECTION (Sample)		7-Nov-08	10-Dec-08	R+R	08520-03-00
	03R	970 SERIES WINDOW SECTION (Sample)		24-Mar-09	30-Mar-09	R	08520-03-01
	04	TRANSLUCENT INSULATING GLASS (Sample)		7-Nov-08	10-Dec-08	R	08520-04-00
	05	CLEAR INSULATING GLASS (Sample)		7-Nov-08	10-Dec-08	R	08520-05-00
	06	SPANDREL GLASS SAMPLE		7-Nov-08	10-Dec-08	R+R	08520-06-00
	06R	SPANDREL GLASS SAMPLE		24-Mar-09	30-Mar-09	R	08520-06-01
	07	Solara Panel Sample		7-Nov-08	30-Mar-09	R	08520-07-00
	08	SHOPDRAWING		5-Dec-08	29-Jan-09	R+R	08520-08-00
	08R	SHOPDRAWING		13-Mar-09	13-Apr-09	R+R	08520-08-01
	08RR	SHOPDRAWING		15-May-09	9-Jun-09	RAM	08520-08-02
	09	METAL FINISH SAMPLE		24-Mar-09	30-Mar-09	R	08520-09-00
	10	WARRANTY FIVE YEARS FOR WORKMANSHIP OR MATERIAL	Close Out				
	11	WARRANTY TEN YEARS GLASS / WINDOW UNIT	Close Out				
08550		WOOD WINDOW	LIMEN GROUP				
	01	SHOPDRAWING		3-Oct-08	18-Dec-08	R+R	08550-01-00
	01R	SHOPDRAWING		26-Aug-09	5-Oct-09	RAM	08550-01-01
	02	WOOD WINDOW PRODUCT DATA		22-Oct-08	5-Oct-09	RAM	08550-02-00
	03	SAMPLE WINDOW FRAME CORNER		22-Oct-08	5-Oct-09	R	08550-03-00
	04	WARRANTY FIVE YEAR	Close Out				
08720		DOOR HARDWARE	EMPIRE HARDWARE				
	01	DOOR HARDWARE SCHEDULE (Ground to 4th)		24-Jul-08	26-Apr-09	RAM	08720-01-00
	02	DOOR HARDWARE CUTSHEET		24-Jul-08	30-Sep-08	RAM	08720-02-00
	03	DOOR HARDWARE SCHEDULE (P3 to P1)		28-Mar-09	11-May-09	RAM	08720-03-00
	04	DOOR HARDWARE SCHEDULE (P3 TO 4th)		6-Jul-09	6-Aug-09	RAM	08720-04-00
09250		GYPSUM BOARD	OAKDALE DRYWALL				
	01	Select Sound Black Acoustic Board		28-May-09	30-Jun-09	RAM	09250-01-00
	02	DPR Finishes Product Data and MSDS		28-May-09	30-Jun-09	R	09250-02-00
	03	Roxul Acoustical Fire Batts		28-May-09	13-Jul-09	RAM	09250-03-00
	04	Dryvit Sample (Sandpebble Fine DPR)		28-May-09	30-Jun-09	R	09250-04-00
	05	Dryvit Colour Chart		28-May-09	30-Jun-09	R	09250-05-00
09510		ACOUSTICAL CEILINGS	OAKDALE DRYWALL				
	01	GEORGIAN SQUARE LAY-IN SAMPLE (CEILING TILE)		16-Sep-08	29-Oct-09	R	09510-01-00
	02	FINE FISSURED SECOND LOOK SAMPLE (CEILING TILE)		16-Sep-08	29-Oct-09	R	09510-02-00
	03	ARMSTRONG PRELUDE CEILING GRID SAMPLE		16-Sep-08	29-Oct-09	R	09510-03-00
	04	SUSTAINABLE INTERIOR FINISHING PRODUCT DATA		16-Sep-08	29-Oct-09	R	09510-04-00
	05	MAINTENANCE MATERIAL 5% EXTRA STOCK	Close Out				
	06	WARRANTY	Close Out				
09640		WOOD FLOORING	WESTPOINT				
	01	SHOPDRAWING		20-Oct-08	11-Nov-08	R	09640-01-00
	02	WARRANTY	Close Out				
09650		RESILIENT FLOORING	LAB CONSTRUCTION				
	01	MAINTENANCE METHODS AND PROCEDURES	Close Out				
	02	TWO FULL CARTONS EACH TYPE USED (STOCK)	Close Out				
09710		ACOUSTICAL TREATMENT					
	01	TECTUM ACOUSTICAL PANELS SAMPLE	OAKDALE DRYWALL	16-Sep-08	29-Oct-09	R	09710-01-00
	02	AVANTI ACOUSTICAL PANEL SAMPLE		16-Sep-08	29-Oct-09	R	09710-02-00
	03	AVANTI ACOUSTICAL PANEL COLOUR CHART		16-Sep-08	29-Oct-09	R	09710-03-00
	04	AVANTI ACOUSTICAL PANEL PRODUCT DATA		16-Sep-08	29-Oct-09	R	09710-04-00
	05	TECTUM ACOUSTICAL PANEL PRODUCT DATA		16-Sep-08	29-Oct-09	R	09710-05-00
	06	TECTUM ACOUSTICAL PANEL LEED PRODUCT DATA		16-Sep-08	29-Oct-09	R	09710-06-00

Appendix A-1: Submittal Log (TDSB)



System Entry Date Stamp

UMM AL-QURA UNIVERSITY
UNIVERSITY MAIN CAMPUS PROJECT
CONSTRUCTION SUPERVISION CONTRACT
SAUDI CONSULTING SERVICES

CERTIFICATE OF COMPLIANCE
MATERIAL TRANSMITTAL FORM - TSF-01

رابية
RABYA Construction

Contract No. ______ Title: SINGLE STUDENT HOUSING BUILDING-2

Contractor: RABYA

We understand that approval of the material(s) submitted herein is only intended to determine general conformance with the intent of the project contract documents. By submitting these materials for approval, we confirm we have performed all necessary on-site dimensional and building utility requirement coordination, and if approval is granted, will further coordinate the information contained within with all other concerned contractors employed by the University.

MATERIAL SOURCE CODES: (S) Saudi Arabia (G) Gulf Cooperative Council (F) Imported

ENG.KHALED TALHOUK, PROJECTS MANAGER

Transmittal No. UQ-SSH-AR-012-2 Transmittal Date: 06/07/2011

Subject: ALUMINUM WORKS

This approval is limited for single student housing

Item	Specs	Prod.	Rev.	Description	Subs.Req.	Source	Action	Comments
	8525		0	ALUMINUM WORKS		S	B	Only first class top quality
				MANUFACTURER / SUPPLIER				Super Saray section
				RABYA				with perfect assembly and
				TEL:02-6602856/02-5281297				Laval accessories and
				FAX:02-6695552/02-5280032				
				P.O BOX:5536,JEDDAH 21432				
				E-MAIL ADDRESS: CONSTRUCTION@RABYA.COM.SA				

The above approval does not relieve the Contractor of any contract obligations, whether for coordination, compliance, or quality with the contract terms and conditions of the contract.

top quality Amircan double, tempered Glass is acceptable

SC Director of Projects Date 19/7/2-11

ACTION CODES:
(A) Approved
(B) Approved As Noted, Resubmittal Not Required
(C) Revise and Resubmit
(D) Not Approved

Contractor Receipt:
Received By Date 24/7/4

MATERIAL SUBMITTAL

Appendix A-2: Submittal Transmittal Form (UQU)

UMM AL-QURA UNIVERSITY
UNIVERSITY MAIN CAMPUS PROJECT
CONSTRUCTION SUPERVISION CONTRACT
SAUDI CONSULTING SERVICES

MATERIAL SUBMITTAL
ROUTING FORM - TSF-01
Sheet 1 of 4
٠٣-يوليو-١١

رابــيــة
RABYA Construction

RECEIVED 06 JUL 2011

System Entry Date Stamp

٣٧

Contract No.: ____________ Title: SINGLE STUDENT HOUSING BUILDING-2

Contractor: RABYA

Transmittal No.: UQ-SSH-AR-012-2 Transmittal Date: 06/07/2011

Subject: ALUMINUM WORKS

Document Type: ☑ Material Submittal ☐ O&M Manual ☑ Sample (ON SITE)

Position	Initial	Date Received	Date Sent	Remarks
Contractor			06 JUL 2011	
Document Control		05 JUN 2011		
SCE		06 JUN 2011	07/07/11	☐ Proceed with Review ☐ Rejected
Tech. Services	Awadi	07 JUL 2011	16/07	TO SCE
☐ Structural				
☐ Mechanical				
☐ Electrical				
☐ Architectural				
☐ Landscaping				
UQU Plan. & Dev.				
SCE		17 JUL 2011	18/07/11	
UQU Proj. Manager				
Const. Manager		18 JUL 2011	18.7.2011	
Director of Projects		19 JUL 2011	19/7/2011	
Document Control				
Contractor		24/7/11		

ACTION CODES:

(A) Approved
(B) Approved As Noted, Resubmittal Not Required
(C) Revise and Resubmit
(D) Not Approved

MATERIAL SUBMITTAL

Appendix A-3: Submittal Transmittal Form (UQU)

SECTION 08525

ALUMINUM ARCHITECTURAL WINDOWS

PART 1 - GENERAL

1.1 DESCRIPTION OF WORK:

A. Furnish and install fixed and operable aluminum architectural windows, where windows are indicated in exterior walls.

B. Applications of Architectural Windows Include:

1. Individual units set in wall construction.
2. Operable units installed in glazed curtain wall.

C. Related Work Specified Elsewhere:

1. Sealants: Section 07900.
2. Glass and Glazing: Section 08800
3. Glazed Curtain Wall: Section 08900

1.2 SYSTEM DESCRIPTION:

A. Performance Requirements: Comply with performance requirements indicated.

1. Air infiltration rate of fixed architectural windows shall not be more than 0.006 $m^3/min/m$ of sash joint for an inward test pressure of 30 kg/m^2, when tested in accordance with ASTM E 283.

2. Water Penetration: When tested in accordance with ASTM E 331 at an inward test pressure of 39 kg/m^2 there shall be no water penetration as defined in ASTM E 331.

3. Uniform Load Deflection: When tested in accordance with ASTM E 330 at a static air pressure difference of 146 kg/m^2, with the pressure applied first on one side of the unit, then

0.006 × 60 = 0.36 $(m^3/h)/m$.

Appendix A-4: Technical Specifications (UQU) on the other, there shall be no permanent deflection in any window member greater than 1/175 of its span.

4. Uniform Load Structural Performance: When tested in accordance with ASTM E 330 at a static air pressure difference of 220 kg/m^2, with the pressure applied first on one side of the unit then the other, there shall be no glass breakage, no permanent damage to fasteners, or hardware parts.

5. Thermal Movements: Capable of withstanding an ambient temperature range of 70 deg. C, which may cause aluminum window framing range of 100 deg. C.

1.3 SUBMITTALS:

A. Shop Drawings: Submit shop drawings for aluminum window including information not fully detailed in manufacturer's standard product data and the following:

1. Elevations of continuous work at 1:50.
2. Typical unit elevations at 1:10.
3. Full size section details of every typical composite member.
4. Anchors.
5. Glazing details.
6. Flashing details and sealant requirements.

B. Product Data: Submit manufacturer's product specifications, technical product data, recommendations and standard details for each type of architectural window unit required. Include the following information:

1. Fabrication methods.
2. Finishing.

C. Samples: Submit pairs of samples of the specified finish on 30cm lengths of window members. Show extremes of range of appearance variations.

The Supervising Agency reserves the right to require additional samples, which show fabrication techniques and workmanship.

Appendix A-5: Technical Specifications (UQU)

Appendix B

Sample Calculation for AHP Weights

UQU

Original Matrix

	U-Value	Air Infiltration	Water Penetration	Visible Transmittance	SHGC
U-Value	1.00	7.00	3.00	3.00	7.00
Air Infiltration	0.14	1.00	5.00	3.00	3.00
Water Penetration	0.33	0.20	1.00	3.00	3.00
Visible Transmittance	0.33	0.33	0.33	1.00	0.14
SHGC	0.14	0.33	0.33	7.00	1.00
SUM =	1.95	8.87	9.67	17.00	14.14

Note: Scale of Comparisons is :

1	Equal importance
3	Moderate importance
5	Strong or Essential importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate levels

Revised Matrix

	U-Value	Air Infiltration	Water Penetration	Visible Transmittance	SHGC	Total SUM	Weights
U-Value	0.51	0.79	0.31	0.18	0.49	2.28	**0.46**
Air Infiltration	0.07	0.11	0.52	0.18	0.21	1.09	**0.22**
Water Penetration	0.17	0.02	0.10	0.18	0.21	0.69	**0.14**
Visible Transmittance	0.17	0.04	0.03	0.06	0.01	0.31	**0.06**
SHGC	0.07	0.04	0.03	0.41	0.07	0.63	**0.13**

Consistency Ratio Calculation

	U-Value	Air Infiltration	Water Penetration	Visible Transmittance	SHGC		Weights	
U-Value	1	7	3	3	7	3.46	0.46	7.58
Air Infiltration	0.14	1	5	3	3	1.53	0.22	7.02
Water Penetration	0.33	0.20	1	3	3	0.90	0.14	6.54
Visible Transmittance	0.33	0.33	0.33	1	0.14	0.35	0.06	5.63
SHGC	0.14	0.33	0.33	7	1	0.75	0.13	5.94

Eigen Value	**6.54**
Consistency Index (C.I)	**0.39**
Random Index (R.I)	**1.12**
Consistency Ratio (C.R)	**0.34**

Eigen Value Calculations :

Multiply the original matrix by the weights matrix, then divide the resulting matrix (column J27-J31) by the weight matrix.

Appendix B-1: AHP Weights Sample Calculation

Appendix C

ENERGY STAR® Requirements for Windows

Natural Resources Canada Ressources naturelles Canada Canada

Climate Zones

ENERGY STAR Requirements for Windows and Doors

Zone	Heating Degree-Day Range	Compliance Paths			
		Energy Rating	or	U-factor	
		Minimum ER (unitless) Maximum U-factor 2.00 W/m²•K (0.35 Btu/h•ft.²•°F)		Maximum U-factor W/m²•K (Btu/h•ft.²•°F)	Windows only Minimum ER (unitless)
A	≤3500	21	or	1.80 (0.32)	13
B	>3500 to ≤5500	25	or	1.60 (0.28)	17
C	>5500 to ≤8000	29	or	1.40 (0.25)	21
D	>8000	34	or	1.20 (0.21)	25

Appendix C-1: Maximum Requirements for the U-Values in Canada (NARC 2010)

U-factor (W/m²•K)	U-factor (Btu/h•ft.²•°F)	R-value (ft.²•h•°F/Btu)
3.40	0.60	1.7
3.20	0.56	1.8
3.00	0.53	1.9
2.80	0.50	2.0
2.60	0.46	2.2
2.40	0.42	2.4
2.20	0.39	2.6
2.00	0.35	2.9
1.80	0.32	3.2
1.60	0.28	3.6
1.40	0.25	4.0
1.20	0.21	4.8
1.00	0.18	5.6
0.80	0.14	7.1
0.60	0.11	9.1

U-factor Conversion to R-value

Appendix C-2: U-value Conversion

Appendix D

Samples of HDDs and CDDs

13

TABLE 1A: STANDARD AND INFILTRATION HEATING DEGREE-DAYS (°C-day/yr) TO DIFFERENT BASE TEMPERATURES						
	Standard DD			Infiltration DD		
City, State	*5 °C*	*10 °C*	*15 °C*	*5 °C*	*10 °C*	*15 °C*
Albuquerque, NM	458	1034	1863	453	994	1754
Amarillo, TX	532	1105	1901	671	1387	2366
Atlanta, GA	239	588	1200	291	673	1284
Birmingham, AL	183	498	1093	180	468	989
Bismarck, ND	2071	3053	4243	2657	3840	5231
Boise, ID	695	1469	2563	715	1502	2593
Boston, MA	662	1419	2417	934	1908	3141
Brownsville, TX	5	46	199	5	46	185
Charleston, SC	103	371	861	107	368	819
Cheyene, WY	1137	2064	3269	1512	2736	4280
Chicago, IL	915	1707	2717	1172	2130	3305
Cleveland, OH	858	1633	2665	1122	2053	3238
Dayton, OH	807	1509	2457	992	1813	2868
Denver, CO	888	1657	2708	913	1677	2705
Des Moines, IA	1162	1946	2945	1391	2288	3399
Detroit, MI	1029	1858	2902	1301	2262	3417
Dodge City, KS	724	1405	2313	948	1827	2969
El Paso, TX	173	492	1058	163	459	980
Fort Worth, TX	123	413	938	131	426	943
Great Falls, MT	1443	2301	3486	1839	2954	4479
Indianapolis, IN	821	1534	2478	1005	1813	2843
Kansas City, MO	662	1276	2102	736	1372	2195
Lake Charles, LA	40	209	570	39	209	552
Las Vegas, NV	126	427	1008	125	416	963
Little Rock, AR	279	698	1339	293	709	1326
Los Angeles, CA	1	38	417	1	29	329
Madison, WI	1436	2346	3467	1705	2716	3917
Medford, OR	370	1080	2173	304	855	1685
Miami, FL	1	14	66	1	13	57
Minneapolis, MN	1626	2554	3664	1959	3049	4324
Nashville, TN	323	795	1519	346	823	1532
New York, NY	496	1451	2051	669	1507	2616
Oklahoma City, OK	378	882	1620	448	1032	1871
Omaha, NE	1007	1761	2724	1209	2073	3142
Phoenix, AZ	18	156	528	16	123	401
Pittsburgh, PA	826	1585	2603	963	1792	2853
Portland, ME	1162	2076	3243	1286	2248	3432
Portland, OR	206	752	1773	214	740	1674
Raleigh, NC	314	767	1468	328	777	1444
St Louis, MO	601	1251	2123	679	1377	2277
Salt Lake City, UT	750	1547	2591	762	1564	2599
San Antonio, TX	41	205	602	41	196	552
Seattle, WA	199	849	2036	200	862	2036
Tallahassee, FL	57	219	580	47	177	455
Tampa, FL	12	62	232	12	58	209
Washington, DC	382	954	1775	439	1066	1932
Edmonton, ALB	2581	3733	5148	3024	4278	5752
Montreal, QUE	1643	2549	3683	2056	3123	4396
Toronto, ONT	1228	2127	3279	1464	2478	3714
Vancouver, BC	277	947	2130	247	866	1924
Winnipeg, MAN	2799	3837	5089	3726	5013	6512

Appendix D-1: Heating Degree Days for Several North American Cities (Sherman 1986)

TABLE 2A: COOLING DEGREE-DAYS (^oC-day/yr) TO DIFFERENT BASE TEMPERATURES USING LATENT BASE ENTHALPY OF 4 Wh/kg

	Standard DD			Infiltration DD		
City, State	*10 °C*	*15 °C*	*20 °C*	*10 °C*	*15 °C*	*20 °C*
Albuquerque, NM	2369	1373	653	2158	1502	1011
Amarillo, TX	2459	1430	681	4505	3506	2663
Atlanta, GA	2733	1520	633	4582	3679	2927
Birmingham, AL	2966	1736	813	4377	3532	2836
Bismarck, ND	1354	721	306	2184	1591	1126
Boise, ID	1634	904	430	1543	1008	624
Boston, MA	1627	799	294	3147	2326	1647
Brownsville, TX	4732	3060	1593	11767	10181	8736
Charleston, SC	3224	1889	847	6218	5152	4229
Cheyene, WY	1195	575	227	1719	1115	652
Chicago, IL	1844	1030	444	2986	2286	1723
Cleveland, OH	1624	831	317	3016	2264	1663
Dayton, OH	1923	1046	419	2958	2258	1699
Denver, CO	1676	903	404	1712	1127	683
Des Moines, IA	1851	1025	432	3168	2497	1952
Detroit, MI	1573	792	276	2475	1838	1322
Dodge City, KS	2297	1381	697	4978	3933	3060
El Paso, TX	3291	2031	1059	3259	2419	1788
Fort Worth, TX	3481	2181	1167	7031	5826	4794
Great Falls, MT	1226	586	227	1288	733	371
Indianapolis, IN	1966	1085	448	3269	2559	1978
Kansas City, MO	2521	1523	761	4241	3447	2784
Lake Charles, LA	3789	2324	1134	7610	6430	5378
Las Vegas, NV	3689	2445	1481	3111	2164	1458
Little Rock, AR	3043	1859	929	4904	4057	3335
Los Angeles, CA	2269	823	153	3716	2507	1572
Madison, WI	1416	713	253	2668	2068	1582
Medford, OR	1563	832	389	1542	1019	649
Miami, FL	5128	3354	1702	9866	8507	7236
Minneapolis, MN	1568	854	350	2982	2317	1767
Nashville, TN	2654	1553	712	4180	3376	2702
New York, NY	1996	1071	419	3326	2544	1909
Oklahoma City, OK	2803	1716	866	6188	5100	4181
Omaha, NE	2046	1183	545	3542	2829	2238
Phoenix, AZ	4516	3063	1892	4107	3222	2501
Pittsburgh, PA	1632	824	296	2509	1851	1332
Portland, ME	1189	531	171	1984	1423	984
Portland, OR	1334	530	169	1788	1081	597
Raleigh, NC	2547	1423	604	3916	3136	2478
St. Louis, MO	2322	1370	646	4389	3588	2924
Salt Lake City, UT	1898	1117	559	1841	1225	767
San Antonio, TX	3862	2433	1259	7003	5838	4838
Seattle, WA	954	316	83	1520	848	416
Tallahassee, FL	3675	2211	1041	5358	4456	3672
Tampa, FL	4360	2705	1326	7903	6641	5495
Washington, DC	2375	1371	603	3867	3108	2465
Edmonton, ALB	637	228	50	802	462	247
Montreal, QUE	1269	578	167	1867	1347	949
Toronto, ONT	1295	623	215	1929	1404	1009
Vancouver, BC	861	218	24	1403	798	393
Winnipeg, MAN	1061	487	159	1852	1268	829

Appendix D-2: Cooling Degree Days for Several North American Cities (Sherman 1986)

TABLE 3A: COOLING DEGREE-DAYS (^oC-day/yr) TO DIFFERENT BASE TEMPERATURES USING LATENT BASE ENTHALPY OF 6 Wh/kg

	Standard DD			Infiltration DD		
City, State	*10 °C*	*15 °C*	*20 °C*	*10 °C*	*15 °C*	*20 °C*
Albuquerque, NM	2369	1373	653	1301	834	503
Amarillo, TX	2459	1430	681	3171	2337	1655
Atlanta, GA	2733	1520	633	3379	2637	2028
Birmingham, AL	2966	1736	813	3256	2562	1976
Bismarck, ND	1354	721	306	1402	955	613
Boise, ID	1634	904	430	848	496	269
Boston, MA	1627	799	294	2053	1398	926
Brownsville, TX	4732	3060	1593	9622	8138	6786
Charleston, SC	3224	1889	847	4791	3858	3048
Cheyene, WY	1195	575	227	924	493	213
Chicago, IL	1844	1030	444	2061	1508	1060
Cleveland, OH	1624	831	317	2022	1440	985
Dayton, OH	1923	1046	419	2033	1489	1051
Denver, CO	1676	903	404	946	526	236
Des Moines, IA	1851	1025	432	2279	1742	1308
Detroit, MI	1573	792	276	1631	1129	754
Dodge City, KS	2297	1381	697	3587	2717	1988
El Paso, TX	3291	2031	1059	2164	1553	1076
Fort Worth, TX	3481	2181	1167	5419	4388	3517
Great Falls, MT	1226	586	227	577	259	97
Indianapolis, IN	1966	1085	448	2328	1754	1292
Kansas City, MO	2521	1523	761	3185	2525	1965
Lake Charles, LA	3789	2324	1134	6020	4950	4000
Las Vegas, NV	3689	2445	1481	1871	1214	765
Little Rock, AR	3043	1859	929	3774	3047	2423
Los Angeles, CA	2269	823	153	2123	1246	653
Madison, WI	1416	713	253	1872	1397	1013
Medford, OR	1563	832	389	865	527	307
Miami, FL	5128	3354	1702	8020	6699	5479
Minneapolis, MN	1568	854	350	2098	1556	1118
Nashville, TN	2654	1553	712	3109	2438	1878
New York, NY	1996	1071	419	2289	1668	1181
Oklahoma City, OK	2803	1716	866	4735	3823	3058
Omaha, NE	2046	1183	545	2594	2011	1531
Phoenix, AZ	4516	3063	1892	2934	2227	1660
Pittsburgh, PA	1632	824	296	1642	1139	747
Portland, ME	1189	531	171	1244	826	526
Portland, OR	1334	530	169	876	443	197
Raleigh, NC	2547	1423	604	2877	2218	1669
St Louis, MO	2322	1370	646	3327	2661	2098
Salt Lake City, UT	1898	1117	559	1036	605	302
San Antonio, TX	3862	2433	1259	5445	4441	3571
Seattle, WA	954	316	83	661	287	109
Tallahassee, FL	3675	2211	1041	4151	3355	2663
Tampa, FL	4360	2705	1326	6197	5027	4003
Washington, DC	2375	1371	603	2854	2214	1683
Edmonton, ALB	637	228	50	369	181	85
Montreal, QUE	1269	578	167	1186	804	526
Toronto, ONT	1295	623	215	1243	868	597
Vancouver, BC	861	218	24	625	271	98
Winnipeg, MAN	1061	487	159	1086	678	391

Appendix D-3: Cooling Degree Days for Several North American Cities (Sherman 1986)

TABLE 4A: COOLING DEGREE-DAYS (°C-day/yr) TO DIFFERENT BASE TEMPERATURES USING LATENT BASE ENTHALPY OF 8 Wh/kg

	Standard DD			Infiltration DD		
City, State	*10 °C*	*15 °C*	*20 °C*	*10 °C*	*15 °C*	*20 °C*
Albuquerque, NM	2369	1373	653	696	392	187
Amarillo, TX	2459	1430	681	2064	1398	886
Atlanta, GA	2733	1520	633	2393	1794	1304
Birmingham, AL	2966	1736	813	2330	1747	1258
Bismarck, ND	1354	721	306	816	494	277
Boise, ID	1634	904	430	398	198	81
Boston, MA	1627	799	294	1201	766	464
Brownsville, TX	4732	3060	1593	7615	6227	4976
Charleston, SC	3224	1889	847	3541	2724	2033
Cheyene, WY	1195	575	227	371	134	27
Chicago, IL	1844	1030	444	1328	895	572
Cleveland, OH	1624	831	317	1254	821	503
Dayton, OH	1923	1046	419	1314	887	561
Denver, CO	1676	903	404	401	153	42
Des Moines, IA	1851	1025	432	1568	1143	807
Detroit, MI	1573	792	276	974	625	378
Dodge City, KS	2297	1381	697	2426	1710	1140
El Paso, TX	3291	2031	1059	1361	897	523
Fort Worth, TX	3481	2181	1167	4044	3175	2443
Great Falls, MT	1226	586	227	183	61	15
Indianapolis, IN	1966	1085	448	1567	1123	783
Kansas City, MO	2521	1523	761	2304	1746	1283
Lake Charles, LA	3789	2324	1134	4579	3618	2795
Las Vegas, NV	3689	2445	1481	1022	618	352
Little Rock, AR	3043	1859	929	2802	2177	1655
Los Angeles, CA	2269	823	153	997	456	153
Madison, WI	1416	713	253	1243	868	580
Medford, OR	1563	832	389	433	235	116
Miami, FL	5128	3354	1702	6228	4973	3849
Minneapolis, MN	1568	854	350	1379	955	619
Nashville, TN	2654	1553	712	2216	1659	1197
New York, NY	1996	1071	419	1471	1000	658
Oklahoma City, OK	2803	1716	866	3522	2751	2071
Omaha, NE	2046	1183	545	1821	1343	948
Phoenix, AZ	4516	3063	1892	1999	1448	1016
Pittsburgh, PA	1632	824	296	979	606	349
Portland, ME	1189	531	171	702	421	244
Portland, OR	1334	530	169	332	135	52
Raleigh, NC	2547	1423	604	1999	1461	1038
St Louis, MO	2322	1370	646	2437	1882	1422
Salt Lake City, UT	1898	1117	559	477	206	62
San Antonio, TX	3862	2433	1259	4100	3220	2447
Seattle, WA	954	316	83	202	69	19
Tallahassee, FL	3675	2211	1041	3083	2388	1801
Tampa, FL	4360	2705	1326	4625	3594	2711
Washington, DC	2375	1371	603	2004	1474	1044
Edmonton, ALB	637	228	50	137	59	23
Montreal, QUE	1269	578	167	689	428	249
Toronto, ONT	1295	623	215	756	501	314
Vancouver, BC	861	218	24	189	58	11
Winnipeg, MAN	1061	487	159	557	294	132

Appendix D-4: Cooling Degree Days for Several North American Cities (Sherman 1986)

Appendix E

Miscellaneous

CSI — Knowledge for Creating and Sustaining the Built Environment

SUBMITTAL TRANSMITTAL

SAMPLE

Project: ___ Date: ___

A/E Project Number: ___

TRANSMITTAL A
To (Contractor): ___ Date: ___ Submittal No. ___
From (Subcontractor): ___ By: ___ ☐ Resubmission

Qty.	Reference / Number	Title / Description / Manufacturer	Spec. Section Title and Paragraph / Drawing Detail Reference

☐ Submitted for review and approval
☐ Resubmitted for review and approval
☐ Complies with contract requirements
☐ Will be available to meet construction schedule
☐ A/E review time included in construction schedule
☐ Substitution involved - Substitution request attached
☐ If substitution involved, submission includes point-by-point comparative data or preliminary details
☐ Items included in submission will be ordered immediately upon receipt of approval

Other remarks on above submission: ☐ One copy retained by sender

TRANSMITTAL B
To (A/E): ___ Attn: ___ Date Rec'd by Contractor: ___
From (Contractor): ___ By: ___ Date Trnsmt'd by Contractor: ___

☐ Approved
☐ Approved as noted
☐ Revise / Resubmit
☐ Rejected / Resubmit

Other remarks on above submission: ☐ One copy retained by sender

TRANSMITTAL C
To (Contractor): ___ Attn: ___ Date Rec'd by A/E: ___
From (A/E): ___ ☐ Other By: ___ Date Trnsmt'd by A/E: ___

☐ Approved
☐ Approved as noted
☐ Not subject to review
☐ No action required
☐ Revise / Resubmit
☐ Rejected / Resubmit
☐ Approved as noted / Resubmit
☐ Provide file copy with corrections identified
☐ Sepia copies only returned
☐ Point-by-point comparative data required to complete approval process
☐ Submission Incomplete / Resubmit

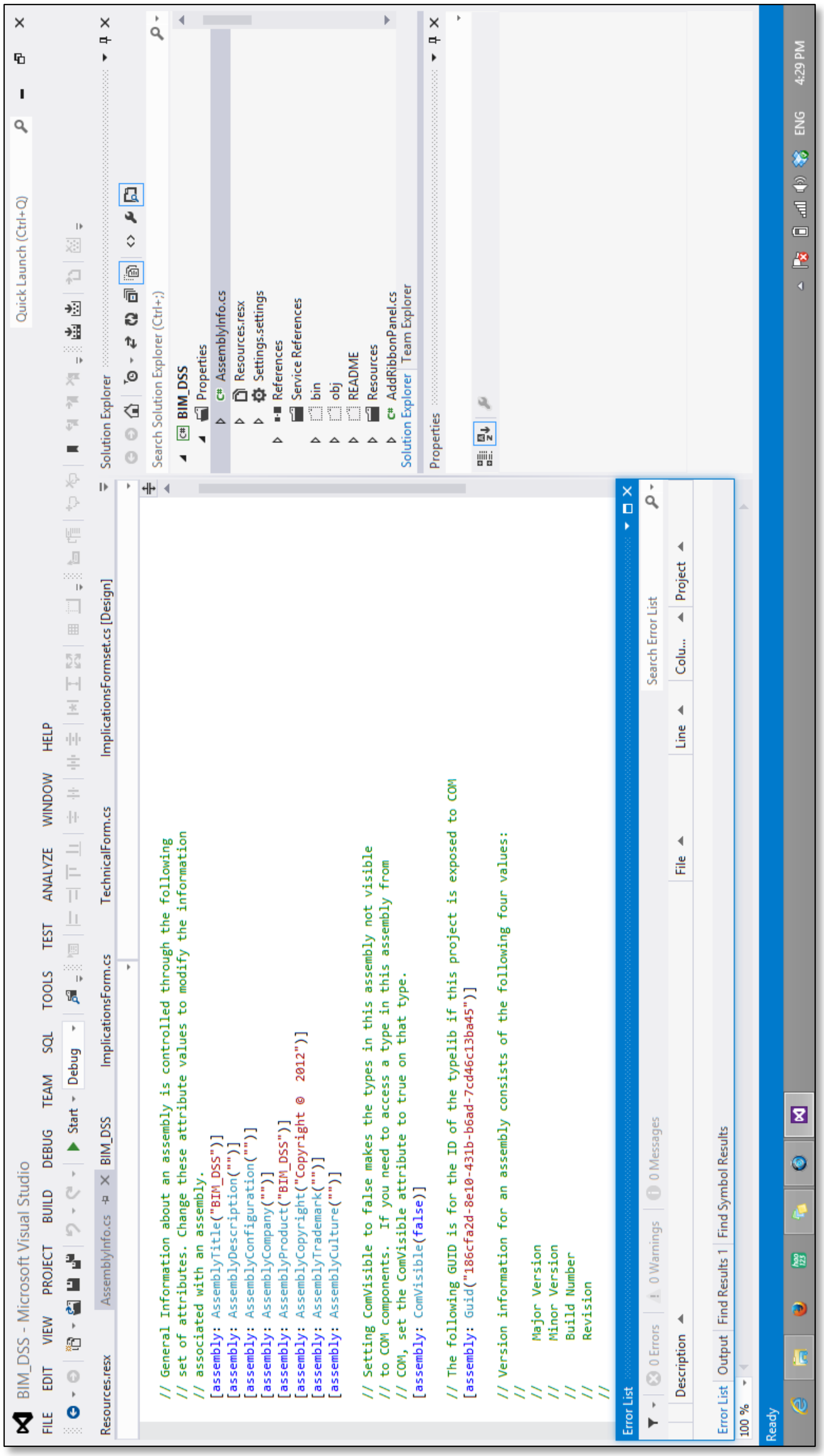
Other remarks on above submission: ☐ One copy retained by sender

TRANSMITTAL D
To (Subcontractor): ___ Attn: ___ Date Rec'd by Contractor: ___
From (Contractor): ___ By: ___ Date Trnsmt'd by Contractor: ___

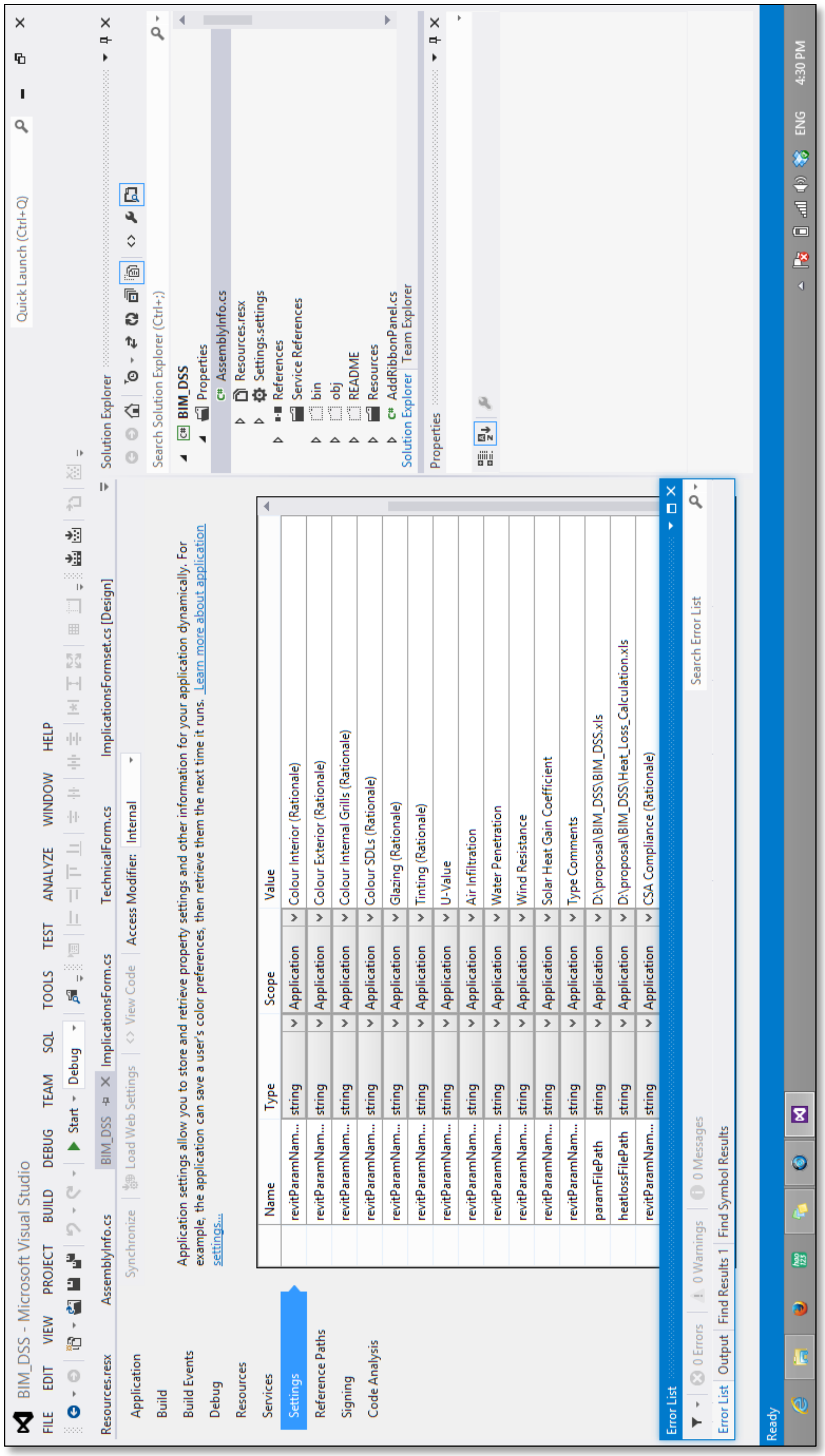
Copies: ☐ Owner ☐ Consultants ☐ ___ ☐ ___ ☐ ___ ☐ One copy retained by sender

Page 1 of ___
September 1996
CSI Form 12.1A

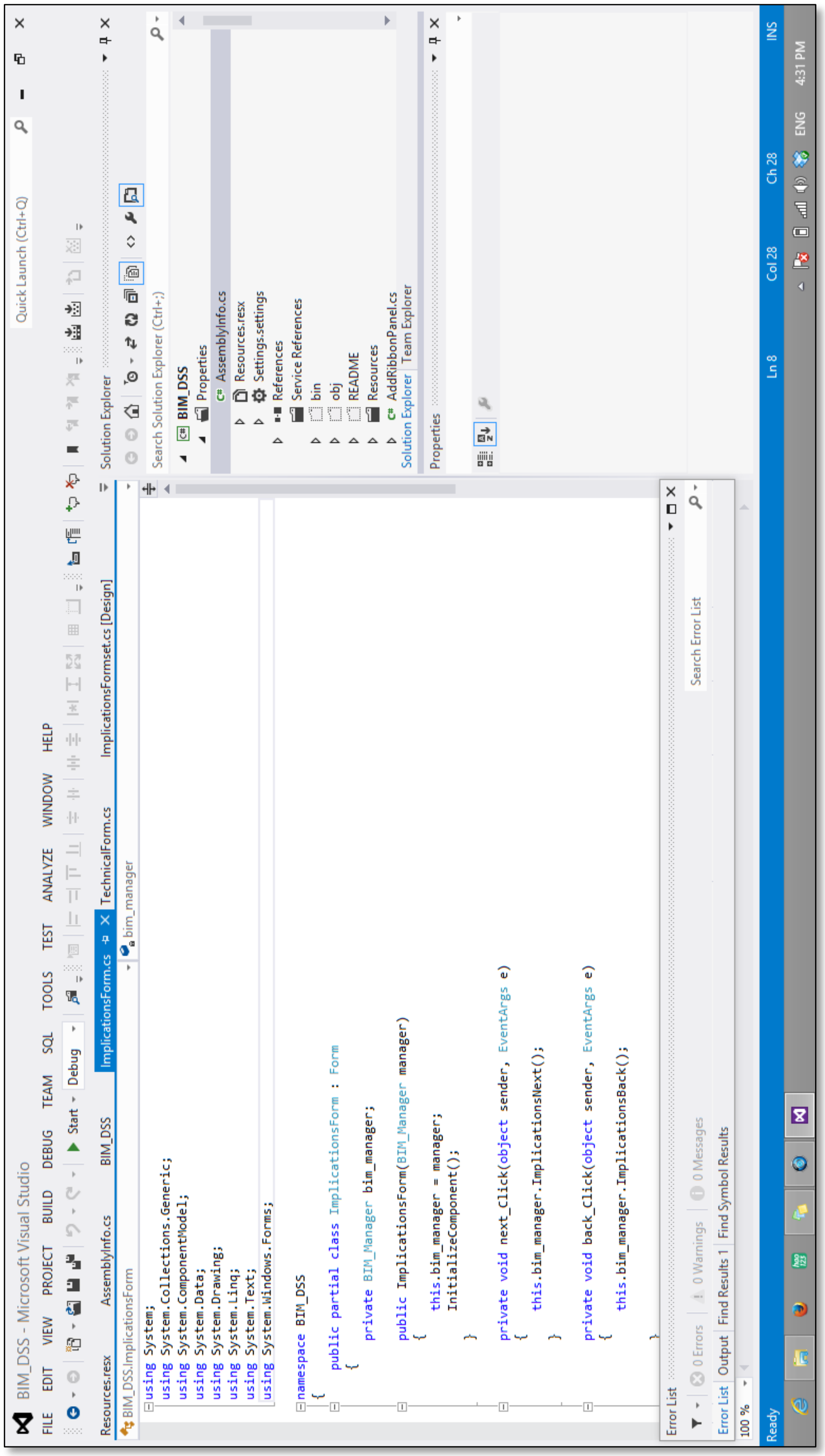
Appendix E-1: Submittal Transmittal Form (CSI 2011)



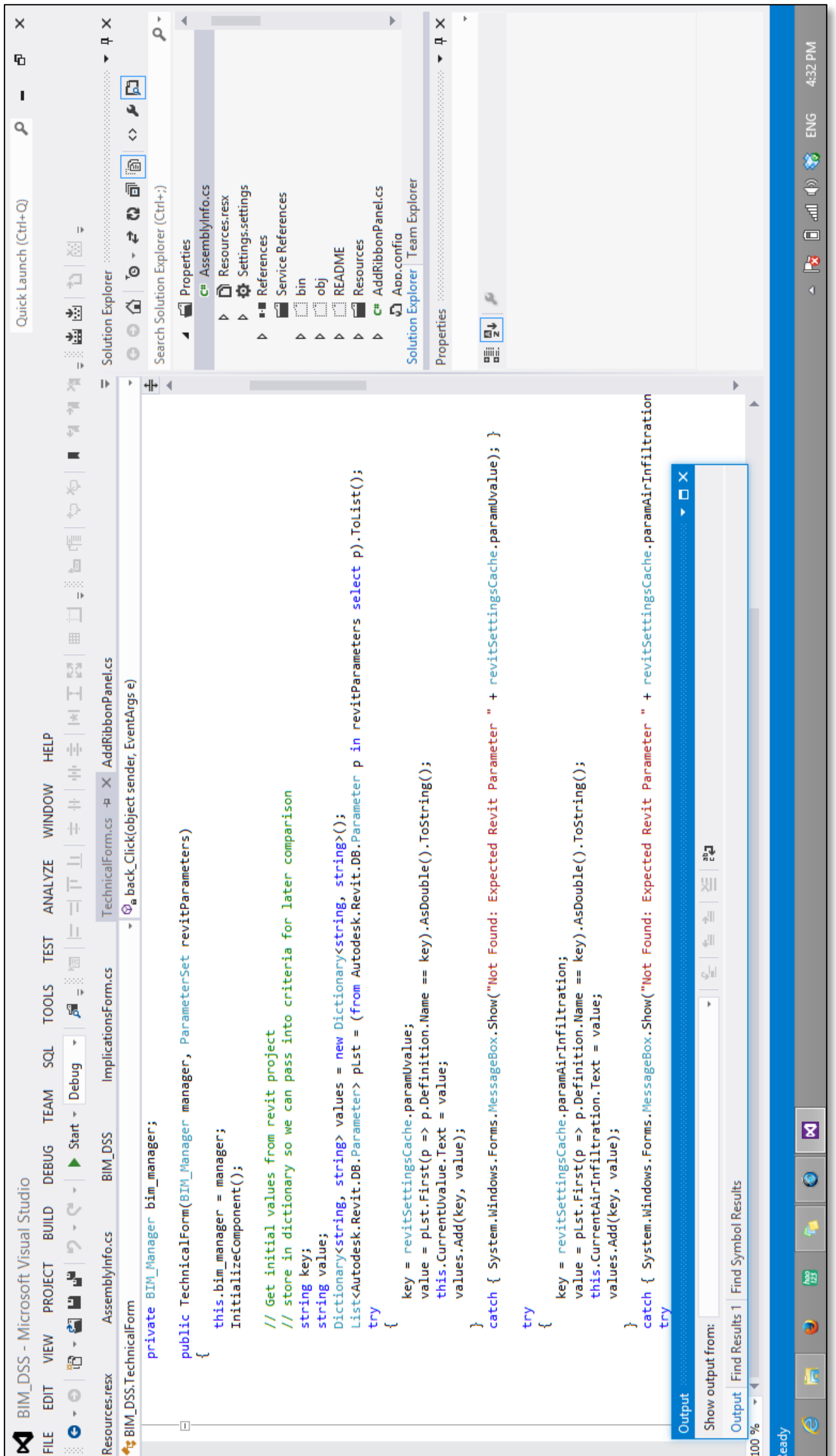
Appendix E-2: Sample of Codes Created in Visual Studio 2012 Programming Environment



Appendix E-3: Sample of Codes Created in Visual Studio 2012 Programming Environment



Appendix E-4: Sample of Codes Created in Visual Studio 2012 Programming Environment



Appendix E-5: Sample of Codes Created in Visual Studio 2012 Programming Environment

	A	B	C	D	E	F
1	U-Value	Air Infiltration	Water Penetration	VT	SHGC	Overall Scores
2	1.64	1.65	700	0.82	0.56	**72.91**
3	1.65	0.55	600	0.78	0.52	**78.11**
4	1.65	0.55	700	0.94	0.54	**80.61**
5	1.65	0.55	600	0.82	0.56	**78.63**
6	1.64	0.55	600	0.76	0.57	**78.64**
7	1.60	0.55	700	0.76	0.47	**84.13**
8	1.62	0.55	700	0.97	0.43	**83.50**
9	1.61	0.55	700	0.93	0.47	**84.91**
10	1.63	1.65	600	0.91	0.42	**74.27**
11	1.67	0.55	700	0.77	0.51	**77.67**
12	1.63	0.55	700	0.71	0.40	**81.34**
13	1.64	1.65	700	0.71	0.58	**71.82**
14	1.67	0.55	700	0.87	0.52	**78.63**
15	1.62	0.55	700	0.83	0.44	**83.42**
16	1.64	1.65	600	0.76	0.58	**70.84**
17	1.68	0.55	700	0.81	0.49	**77.24**
18	1.63	0.55	600	0.93	0.40	**81.64**
19	1.61	0.55	600	0.93	0.46	**83.57**
20	1.66	0.55	700	0.91	0.53	**79.33**
21	1.64	0.55	700	0.69	0.58	**79.74**
22	1.63	1.65	700	0.94	0.60	**73.70**
23	1.61	0.55	700	0.81	0.44	**83.52**
24	1.67	1.65	600	0.97	0.51	**69.47**
25	1.65	0.55	700	0.93	0.55	**79.82**
26	1.67	0.55	700	0.91	0.50	**78.12**
27	1.60	0.55	700	0.82	0.48	**84.80**
28	1.62	1.65	700	0.89	0.43	**75.55**
29	1.63	0.55	600	0.89	0.40	**81.56**
30	1.66	0.55	700	0.74	0.54	**78.63**
31	1.67	0.55	700	0.92	0.50	**78.38**
32	1.62	1.65	700	0.86	0.44	**75.81**
33	1.65	0.55	700	0.91	0.55	**80.05**
34	1.64	1.65	700	0.98	0.57	**73.01**
35	1.68	0.55	700	0.80	0.49	**77.16**
37	1.63	1.65	700	0.87	0.41	**74.96**
38	1.62	0.55	600	0.81	0.42	**81.68**
39	1.66	1.65	600	0.81	0.52	**69.50**
40	1.66	0.55	700	0.83	0.53	**78.86**
41	1.64	0.55	700	0.79	0.57	**80.00**
42	1.66	0.55	600	0.77	0.52	**77.06**
43	1.67	1.65	600	0.68	0.50	**68.13**
44	1.61	0.55	600	0.75	0.45	**82.27**
45	1.62	0.55	700	0.76	0.43	**82.68**
46	1.65	1.65	700	0.92	0.57	**72.72**
47	1.66	0.55	700	0.79	0.53	**78.54**
48	1.63	1.65	700	0.91	0.41	**75.16**
49	1.64	0.55	700	0.77	0.58	**80.10**
50	1.63	0.55	700	0.84	0.60	**81.34**
51	1.67	0.55	600	0.98	0.51	**77.56**
52	1.64	0.55	600	0.96	0.58	**79.95**
53	1.62	0.55	700	0.74	0.43	**82.79**
54	1.67	1.65	700	0.81	0.50	**69.89**
55	1.65	1.65	700	0.99	0.55	**72.06**
56	1.65	0.55	700	0.70	0.55	**78.87**
57	1.63	1.65	700	0.98	0.60	**73.73**
58	1.65	1.65	700	0.96	0.55	**72.03**
59	1.66	1.65	700	0.87	0.53	**71.28**
60	1.60	0.55	700	0.94	0.47	**85.17**
61	1.61	0.55	700	0.94	0.45	**84.45**
62	1.62	1.65	700	0.70	0.43	**74.67**
63	1.65	1.65	700	0.97	0.55	**72.29**
64	1.62	1.65	700	0.77	0.43	**75.20**
65	1.65	0.55	700	0.82	0.55	**79.49**
66	1.62	0.55	600	0.71	0.42	**81.23**
67	1.66	1.65	700	0.85	0.53	**71.38**
68	1.65	1.65	700	0.69	0.55	**70.99**
69	1.67	1.65	700	0.74	0.51	**69.88**
70	1.66	1.65	600	0.99	0.52	**70.23**
71	1.64	0.55	700	0.86	0.57	**80.48**

Appendix E-6: Sample of Monte Carlo Simulation Scenarios for Option 1

	U-Value	Air Infiltration	Water Penetration	VT	SHGC	Overall Scores
2	1.64	0.55	700	0.52	0.58	**78.46**
3	1.68	1.65	700	0.85	0.48	**69.28**
4	1.66	0.55	600	0.60	0.53	**76.02**
5	1.61	0.55	700	0.93	0.66	**83.62**
6	1.69	0.55	700	0.96	0.45	**76.53**
7	1.63	0.55	600	0.87	0.62	**80.93**
8	1.66	0.55	700	0.69	0.54	**78.28**
9	1.61	1.65	700	0.81	0.66	**75.14**
10	1.74	1.65	700	0.90	0.32	**64.14**
11	1.64	0.55	700	0.82	0.57	**80.23**
12	1.72	0.55	700	0.70	0.37	**72.60**
13	1.73	0.55	700	0.90	0.36	**73.53**
14	1.75	1.65	700	0.57	0.69	**59.57**
15	1.70	0.55	700	0.56	0.42	**73.52**
16	1.68	0.55	700	0.51	0.49	**75.57**
17	1.73	0.55	700	0.78	0.35	**72.63**
18	1.60	0.55	700	0.73	0.67	**82.83**
19	1.60	1.65	700	0.79	0.67	**75.42**
20	1.61	0.55	700	0.52	0.68	**81.24**
21	1.71	0.55	700	0.86	0.41	**74.75**
22	1.64	0.55	700	0.88	0.60	**81.11**
23	1.64	1.65	600	0.72	0.58	**70.56**
24	1.67	0.55	700	0.54	0.51	**75.71**
25	1.63	0.55	700	0.66	0.62	**80.45**
26	1.60	0.55	700	0.76	0.68	**82.95**
27	1.75	0.55	700	0.74	0.32	**70.84**
28	1.63	1.65	700	0.84	0.63	**73.89**
29	1.63	1.65	700	0.54	0.62	**71.76**
30	1.66	0.55	700	0.70	0.55	**78.39**
31	1.60	0.55	700	0.69	0.68	**82.50**
32	1.74	0.55	700	0.64	0.35	**71.14**
33	1.75	1.65	600	0.63	0.32	**61.06**
34	1.67	1.65	600	0.86	0.53	**69.65**
35	1.66	0.55	600	0.92	0.53	**77.77**
36	1.69	0.55	600	0.94	0.47	**75.87**
37	1.75	0.55	700	1.00	0.31	**71.57**
38	1.67	1.65	700	0.53	0.50	**67.85**
39	1.72	1.65	700	0.66	0.38	**64.46**
40	1.76	0.55	700	0.96	0.70	**69.35**
41	1.71	0.55	700	0.60	0.42	**73.32**
42	1.68	0.55	700	0.69	0.48	**75.87**
43	1.62	0.55	700	0.89	0.62	**82.10**
44	1.71	1.65	700	0.77	0.42	**66.75**
45	1.71	0.55	600	0.97	0.41	**74.02**
46	1.74	0.55	700	0.64	0.34	**71.08**
47	1.69	0.55	600	0.63	0.47	**74.30**
48	1.61	1.65	700	0.79	0.65	**74.46**
49	1.67	1.65	700	0.56	0.51	**68.58**
50	1.70	0.55	700	0.51	0.43	**73.18**
51	1.70	0.55	700	0.57	0.43	**73.60**
52	1.75	0.55	600	0.89	0.31	**70.72**
53	1.69	0.55	700	0.73	0.44	**75.77**
54	1.62	0.55	700	0.76	0.63	**82.13**
55	1.62	0.55	700	0.60	0.61	**80.55**
56	1.65	0.55	600	0.90	0.54	**78.76**
57	1.65	0.55	700	0.82	0.55	**79.78**
58	1.63	0.55	700	0.91	0.61	**82.28**
59	1.68	1.65	700	0.83	0.46	**69.13**
60	1.65	0.55	700	0.99	0.55	**80.45**
61	1.65	1.65	700	0.70	0.54	**71.07**
62	1.63	0.55	700	0.58	0.58	**79.46**
63	1.74	0.55	600	0.57	0.31	**68.88**
64	1.72	0.55	700	0.52	0.38	**72.26**
65	1.61	1.65	700	0.79	0.64	**75.01**

Appendix E-7: Sample of Monte Carlo Simulation Scenarios for Option 3