Multiple-Criteria BIM-based evaluation of architectural submittals

Ibrahim Albukhari and Tarek Hegazy

***Abstract*—** Submittal evaluation is a formal process to measure the compliance of contractor-proposed materials, equipment, and processes before they can be used in a project. For monumental projects that involve unique architectural components, contractors often submit alternatives that may involve minor deviations from designer's requirements. Thorough evaluation is therefore necessary to save project time and quantify the best-value acceptance conditions considering short-term and long-term implications, without compromising design rationale or performance. Thus, this paper develops a structured decision-support framework to help evaluate key architectural submittals during construction in an efficient and speedy manner. First, sample submittal logs were analyzed and architectural windows are defined as key architectural submittals. The research then proposed a mechanism to use Building Information Models (BIM) to store design rationale and specification data within its 3D model of a building. The proposed framework then utilized the multi-attribute utility theory (MAUT) to evaluate the compliance of window submittals with design rationale and performance-related criteria, in addition to computing the overall utility of a submittal and its related life cycle cost. The proposed framework uses this data and applies the multi-attribute utility theory (MAUT) and the analytical hierarchy process (AHP) to evaluate the degree of submittal compliance with design rationale and performance criteria. Accordingly, it suggests correct acceptance conditions, based on analysis of the cost and time implications at the short-term and the long-term during operation. Applying the framework to a case study shows its ability to determine the best-value decisions. The integration of BIM with decision analysis enabled efficient automation of the submittal evaluation process, thus saving time and reducing subjectivity. In addition, storing the design rationale and performance-related criteria in the BIM enabled dynamic updating of specifications with the data of approved submittals, thereby facilitating better operation of buildings.

***Keywords*—**Building Information Model (BIM), Design Rationale, Decision Support, Submittals, Windows, Utility functions

I. INTRODUCTION

THE quality of drawings and specifications generated during the design stage of a project has a large impact on the construction and operation stages of building projects. This effect is clearly indicated in a study by Josephson and Hammarlund [1], which revealed that approximately 30% of all defects that arose during construction and 55% of all defects that appeared during operation are due to design defects. Although both drawings and specifications (which embody all of the design details) are important for construction [2, 3], specifications receive less attention during design and thus become a main cause of construction disputes [4].

Prior to installation, submittal review is a formal process that evaluates all of the material, equipment, and processes submitted by a contractor for compliance with specifications. As part of quality assurance during construction, contractors are required to submit samples of materials or products and follow the formal submittals review/evaluation process. This necessary process 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" [5, 6]. Although submittals are not included as part of contract documents, they must be scheduled and provided by the contractor during construction for all building systems and components [7]. Submittals can be material samples, shop drawings, schedules, equipment, products, and catalogues. The evaluation of these submittals can be a difficult task [8] due to time constraints (typically 14 days); missing information in the submittal package [9]; problems in interpreting design intent in the case of vague specifications; and lack of defined evaluation criteria [10, 11]. Thus, under mounting deadline pressure, the tendency to accept items that appear to have only trivial deviations from specifications can culminate in a sizable negative impact on project performance during construction and operation stages. Therefore, a structured process for speedy and thorough evaluation of submittals is needed to save project time and bring best value to the project.

Among the various types of submittals, architectural components can be among the most difficult to evaluate. They uniquely involve aesthetic requirements (e.g., colour level, style, texture, material, etc.) that require a high degree of subjectivity and experience in their evaluation. One key challenge to the evaluation process is the fact that the design rationale is never documented and, as such, it becomes difficult to decide if a submittal is consistent with the intention of the design especially in cases of submittals with minor changes. Furthermore, architectural components that are part of the building enclosure are the most critical. Leak, a major concern in buildings, is often caused by the architectural windows [12]. Whether the leakage is water or air, the problem remains significant. While water leakage can cause

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severe damage to building structure, air leakage can cause energy waste and discomfort. The energy consumed to compensate unwanted heat loss or gain through window was reported to 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 [12].

Increasing efforts to control submittals have become apparent in the industry, although more on the commercial level than the research level. Submittal management systems are often part of a construction document-management system. Such systems mainly manage the submittal register, track submittals, and save time on data entry and follow-up. Despite their usefulness, however, most systems lack decision support capabilities for submittal evaluation that consider compliance issues and the construction / operational implications of accepting or rejecting submittals. A list of major submittal management tools is provided in Table 1.

To facilitate submittal evaluation, several studies in the literature have reported the importance of documenting the design rationale for preventing violation of the design's original intent [13, 14, 15, 16]. Since submittals can lead to changed items during construction, documentation of design rationale is necessary for the evaluation of submittals. However, to the authors' knowledge, no previous efforts in the literature have proposed or utilized adequate design rationale documentation to facilitate the evaluation of submittals.

Having an accurate centralized depository of project documents and specifications is useful to the submittal evaluation process. In recent years, active research has promoted BIM to replace CAD as a more powerful depository of building information [17, 18]. In essence, BIM provides AEC professionals with both a geometrically accurate 3D representation of a building and also the capability to integrate attributes and data for the components inside the model. Being parametric-based (as opposed to geometric-based in traditional CAD) makes BIM more suitable for the implementation of design changes and for its ability to embed analytical features into the model. Due to its powerful data depository features, this paper develops a framework that combines BIM and a decision analysis tool to document design rationale and performance-related criteria in the BIM platform and facilitate the evaluation of building submittals.

II. Research Objective and Methodology

The aim of this research is to develop a BIM-based decision support framework to help decision makers efficiently evaluate architectural submittals. Detailed objectives are as follows:

- Document design rationale and key criteria;
- Integrate BIM with decision analysis;
- Analyze short-term and long-term implications of accepting borderline submittals;
- Suggest best-value selection of a submittal; and
- Update the BIM to facilitate building operation.

Table 1: Submittal-related software

Tool	Description
SUBMIT [19]	Manages and stores active and non-active submittals.
Newforma [20]	Collaborative software for review and evaluation of shop drawings captured from BIM files.
Submittal Exchange [21]	Manages all construction communications including submittal reviews.
BuildSite [22]	Online system that reduces time for submittal preparation.
AccuBuild [23]	A project management module to track submittal logs.

The paper begins with an analysis of sample real-life submittal logs to define the top architectural submittals. The research then identifies the different levels of criteria to use in the evaluation, including design rationale that capture the subjective aspects of submittal evaluation; and performance-related criteria that relate to construction and operational implications. Thus, a new submittal evaluation framework is proposed which uses BIM to store design rationale, update specification data, and facilitate the evaluation of submittals. The framework utilizes the multi-attribute utility theory (MAUT) to evaluate the compliance of a submittal with design rationale and performance-related criteria, in addition to computing the overall utility of a submittal and its related life cycle cost.

III. Data Analysis: Identifying Key Submittals

Data for this study were collected with the goal of defining the most critical architectural items requiring special consideration during the submittal evaluation process. Experts from two governmental organizations participated in this study: the Toronto District School Board (TDSB) and the Umm Al-Qura University (UQU) Department of Project Management in Saudi Arabia. The TDSB owns, operates, and maintains more than 550 schools in the Toronto area, while the UQU handles projects valued at approximately $258 million for the new UQU campus, including multi-level institutional buildings, an academic hospital, and housing for faculty members. Four experts from two other private A/E firms with experience in commercial, residential, and institutional buildings as well as design and construction management of public and private projects also participated in the study. Collectively, these professionals have extensive experience in reviewing and approving architectural submittals, and more than 10 years of experience working in the construction industry. Surveys were completed during face-to-face interviews, and sample submittal logs were collected and used for further analysis.

The process of identifying the critical architectural submittals involved two steps: analysis of collected submittal logs, and soliciting feedback from experienced practitioners. In the first step, complete sets of submittal logs for two projects (358 submittals) were analyzed to identify the critical architectural submittals. The initial analysis indicated that architectural submittals reserved the largest number of submitted items with 233 records (65%). Mechanical submittals held the second rank with 20% of all submittals, followed by 8% and 7% of structural and electrical submittals, respectively. Figure 1a shows the initial analysis of all recorded submittals. Further analysis of architectural works in the collected logs identified submittals in 11 specific divisions of MasterFormat list, as shown in Figure 1b. The analysis revealed that "Masonry" involved the largest number of submittals (22%), followed by "Openings" (20%). After presenting these results to the practitioners, the "Openings", particularly "Architectural Windows", were considered as most critical due to their large impact on the overall performance of the building (i.e., energy consumption during operation); require rigorous procurement and testing; require specialized fabrication, installation, and maintenance; and hold great aesthetical value.

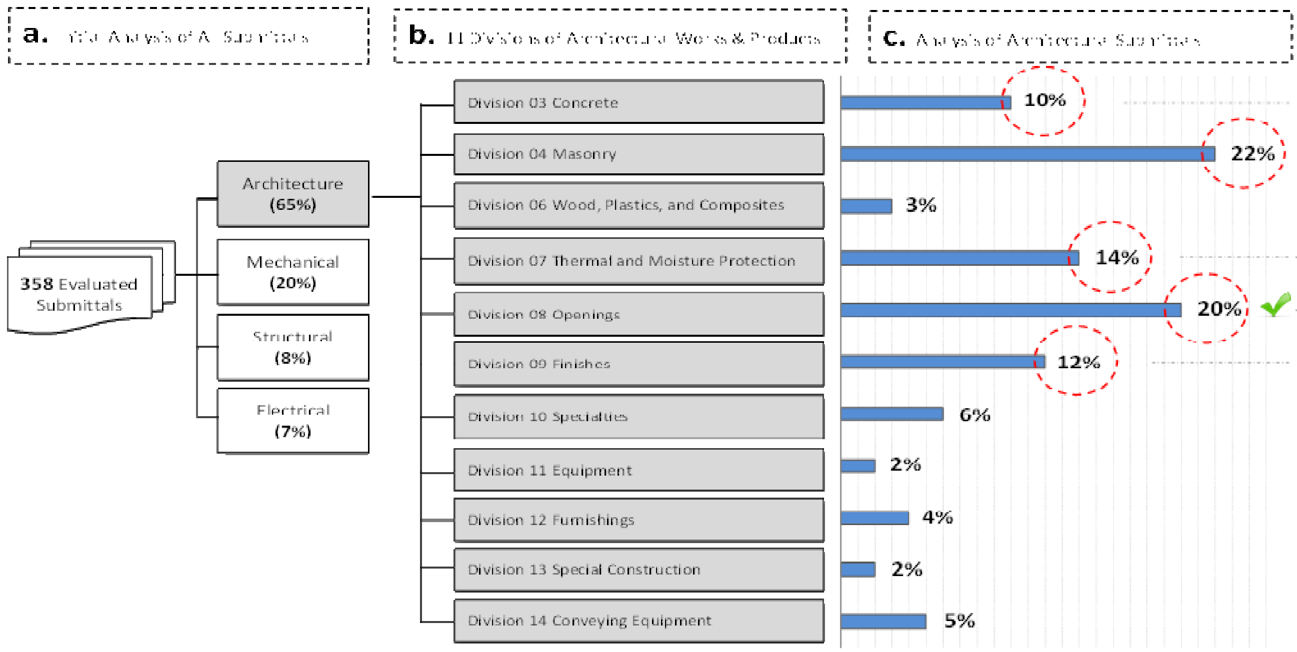

Fig. 1: Analysis of submittal logs

III. Proposed Submittal Evaluation Framework

The basic premise of the proposed framework is that it is sometimes beneficial to conditionally accept a submittal with trivial deviation from specifications (referred to in this research as borderline item) if it provides good project value and does not affect the life cycle economics of the building. However, these submittals must comply with design rationale criteria and satisfy performance-related criteria as determined through a detailed analysis. A conditional acceptance in this case means that the project should be compensated for any additional costs associated with accepting these items. A borderline item that appears to be acceptable during construction phase may produce undesirable effects during operation and may eventually cost more money over the lifecycle of the building [10]. Therefore, construction-related impact (e.g., extra handling/installation charges) and operation-related impact (e.g., extra energy consumption) need to be estimated for borderline submittals and considered as a basis for compensation (e.g., price reduction) as a condition for acceptance. Developing the proposed submittal evaluation framework involved two main phases: Setup and Evaluation (Fig. 2), with their details explained along a case study in the next section.

As shown in Fig. 2, the setup phase is performed before construction starts, and includes defining the weights and utility functions of performance-related criteria, setup of the calculation of implications, and deciding minimum acceptance threshold. These were defined initially for Canada (can be adjusted for each new project based on standards, project location/zone, and levels of required performance). In this step, MAUT was utilized to generate a utility function for each of five criteria suitable for window evaluation, as shown in Fig. 2, based on the CSA-A440-00 performance standard for windows [24], and input from the consulted experts. To determine the relative importance of these criteria, pair-wise comparison using the Analytical Hierarchy Process (AHP) of Saaty [25, 26] were conducted to define their relative weights. Both the utility functions and their weights were then utilized to evaluate the overall scores (utilities) for any submittal. Details on the evaluation process are discussed alongside the description of a case study in the next section of this paper.

The second step in the setup phase of the proposed framework involved customizing the BIM platform to enable the storing and automated access to the specification data of building components (as shown in Fig. 4). Customization also involved storing the design rationale and performance-related criteria for the critical architectural items into the 3D-model of BIM. These data are recorded as custom attributes associated with the parametric properties of 3D items. In this framework, design rationale is represented by a set of rationale criteria with each having a **range of acceptability** (e.g., acceptable patterns, colors, etc.) which designers set based on design concept, preferences, project type, etheric impact, etc. These criteria and their ranges capture the subjective aspects that are not properly documented in building designs. For instance, the design rational for a desired "grey" color can be defined with an acceptable range for the color RAL values (according to the European standards) of 7037 to 7045. This simple approach of storing and design rationale suitably documents the range of design intent. Fig. 4 shows the list of all the performance-related and design-rationale related criteria that was customized into BIM.

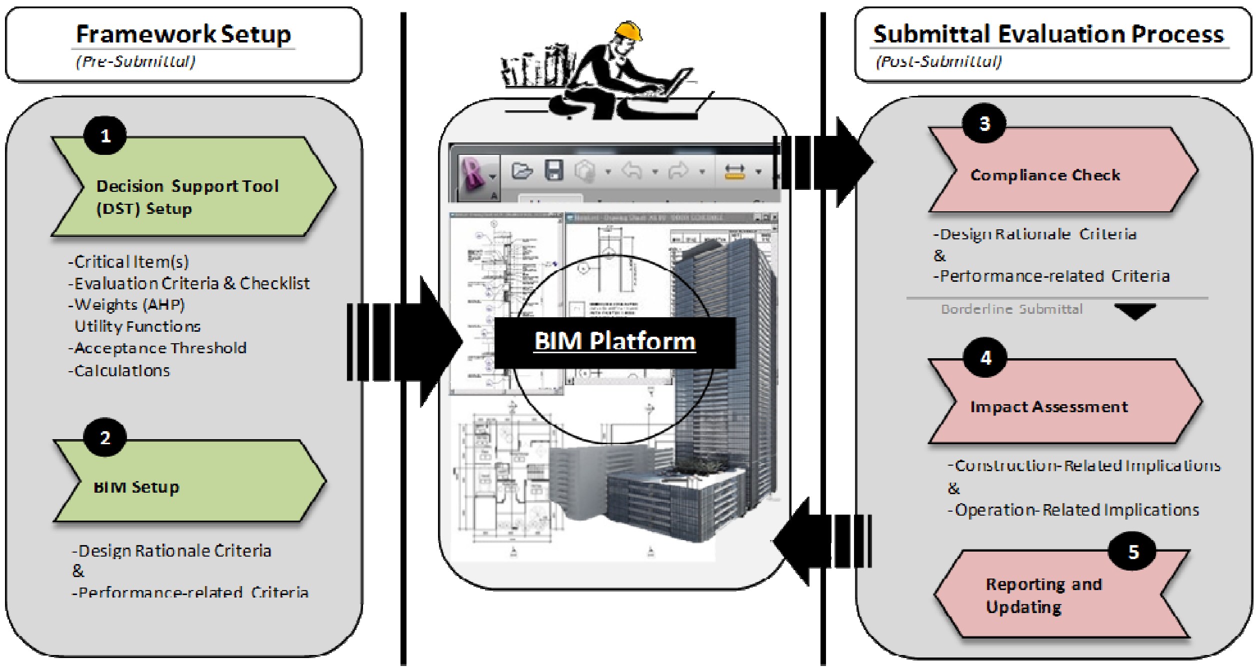

Fig. 2: Proposed framework

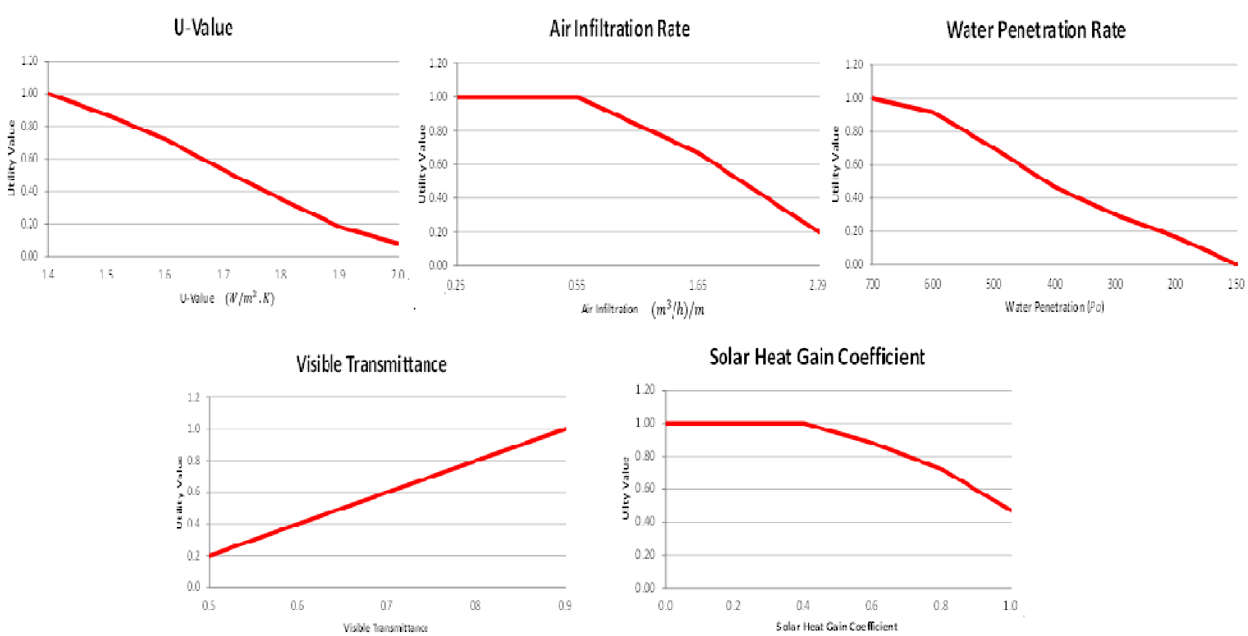

Fig. 3: Utility functions for performance evaluation of windows

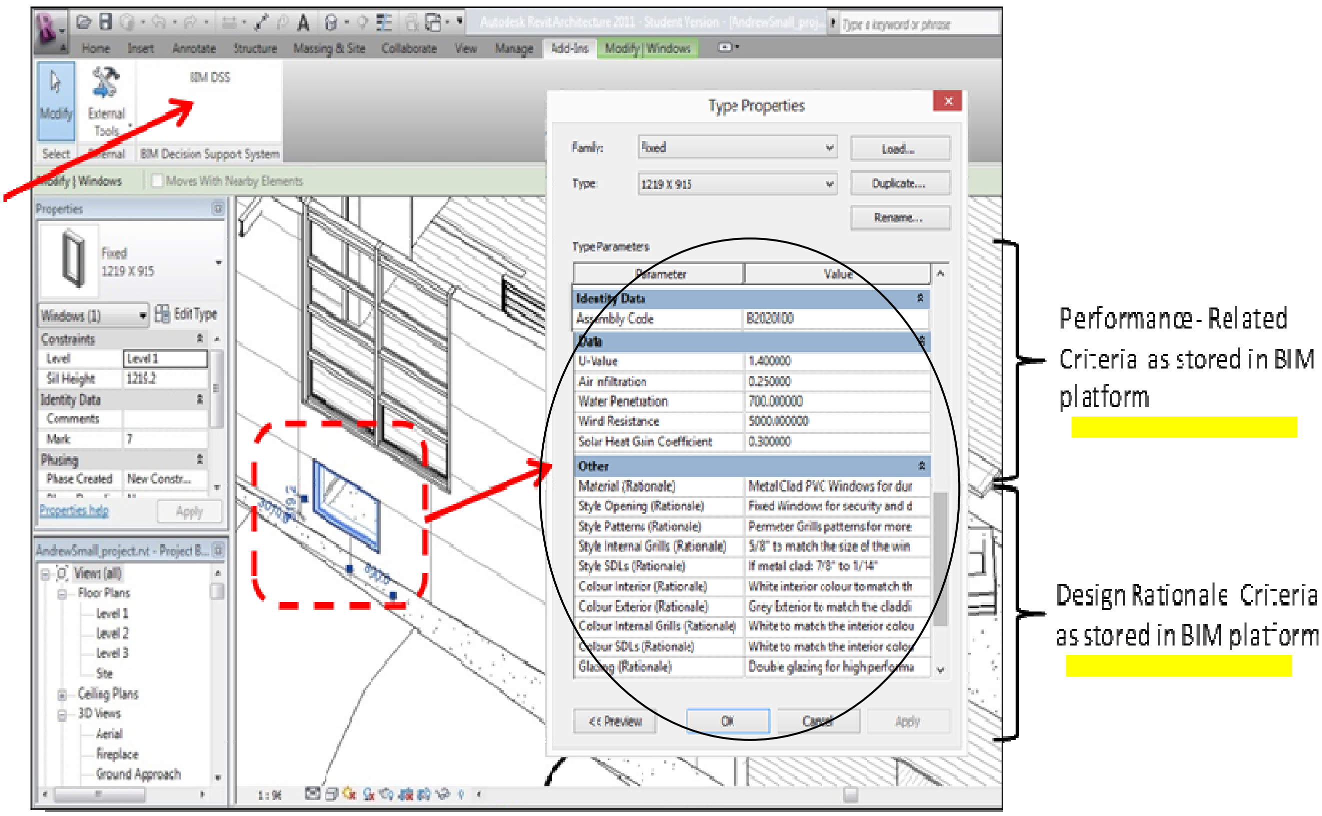

Fig. 4: BIM setup with design rationale

The evaluation phase (right side of Fig. 2) is performed during construction in three steps: “Compliance Check”, “Impact Assessment”, and “Reporting and Updating”. First, analysis of compliance requires observance of both the design rationale and the performance-related criteria of the submittal under evaluation. Items not complying with the design rationale criteria are rejected without further analysis. After passing the design rationale, the submittal is evaluated in terms of technical aspects. To facilitate this step, the overall score (utility) of a submittal is calculated by multiplying the weights and utility scores (determined from the utility curves) and summing all performance-related criteria, which must meet a predefined threshold in order for the item to be conditionally accepted. More explanation is presented in the case study later. Acceptable borderline submittal options are then assessed in terms of their impacts on construction and operational costs. “Construction-Related Implication” is concerned with quantifying all construction costs and delays resulting from accepting borderline submittals. Also, “Operation-Related Implication” is concerned with forecasting all of the additional operation-related costs along the life-cycle of the building. During the “Reporting and Updating” step, all information of the acceptable submittals is presented in a final report for decision making; finally, the specification of the approved option is sent back to update the BIM platform.

IV. Example Application

Revit Architecture 2011 was used in this research as the BIM tool due to its popularity, ease of use, and programmability. The Application Programming Interface (API) of Revit was used to customize and integrate Revit with MS Excel in order to retrieve and save project data in BIM. The add-in feature of Revit API plays a significant role in facilitating the framework of this study. The system has been implemented for evaluating window submittals with the utility functions, design rationale, and performance-related criteria discussed alongside the description of a hypothetical case study. In the case study, a contractor examines three window options that are readily available in the market. Each option slightly violates the required U-value of 1.4. Because obtaining the exact item could delay the project, the contractor is interested in evaluating the condition for accepting these options. To start the process, the contractor selects a window object in Revit and activates the evaluation process. Fig. 5 shows the submittal initiation screen with the general submittal information. As shown in the figure, the window-to-wall ratio (WWR) for the building is 0.60. The framework automatically calculated the total surface areas of walls (including windows) as 3,750m2. The roof area is 1,200m2.

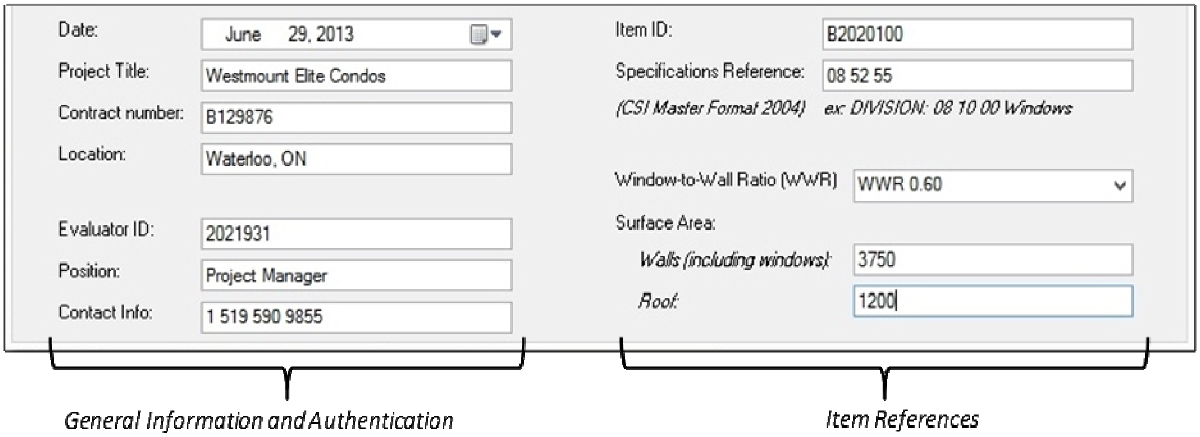

Fig. 5: Initiation of a submittal evaluation

The first step of the evaluation process checks the compliance with design rationale. Fig. 6 shows the evaluation form where the stored rationale criteria in Revit (Fig. 4) are listed on the left. Each of the three submittal options is checked for compliance simply through a Yes/No answer. In this example, all three submittal options were compliant with the design rationale criteria. Thus, the process continues to check performance-related criteria. In this step, the user is required to enter the technical specifications of the proposed submittals. Fig. 7a shows the five technical properties of three window options and their automatically calculated performance scores. The score values (0 to 1.0) are first calculated for each criterion separately based on its utility curve. Fig. 7b shows the utility curve for the "U-value" criterion (generated according to U-values suggested for the province of Ontario, Canada). Such a curve is drawn by plotting at least two points: best and worst. A window with a U-value of 1.4 W/m2°K receives best utility score of 1.0 (best performance), while a window with a U-value of 2.0 W/m2°K receives a score of 0.08 (worst performance). Thus, a window with any U-value ranging between 1.4 W/m2°K and 2.0 W/m2°K receives a score between 1.0 and 0.08. In this example, other utility curves were generated for the other four criteria: air infiltration, water penetration, visible transmittance, and solar heat gain coefficient.

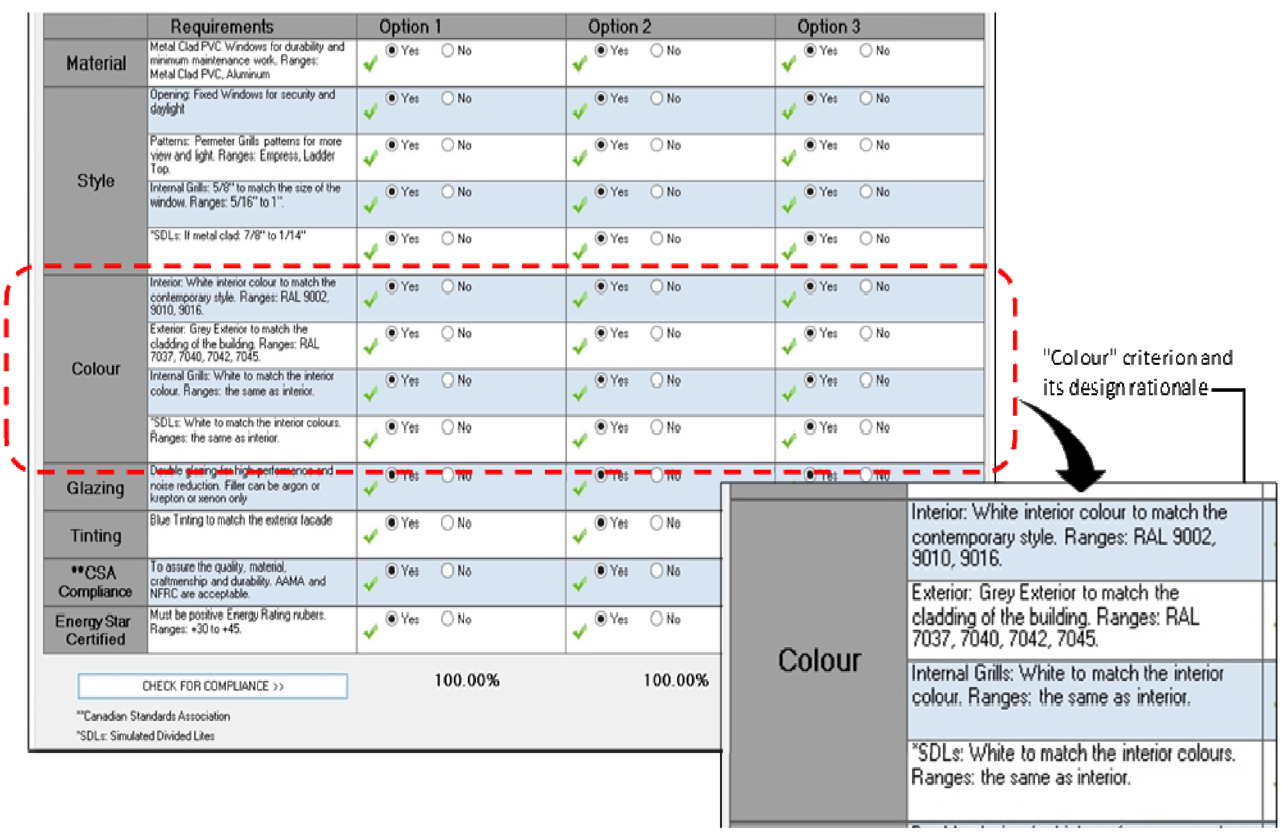

Fig. 6: Checking the compliance with design rationale

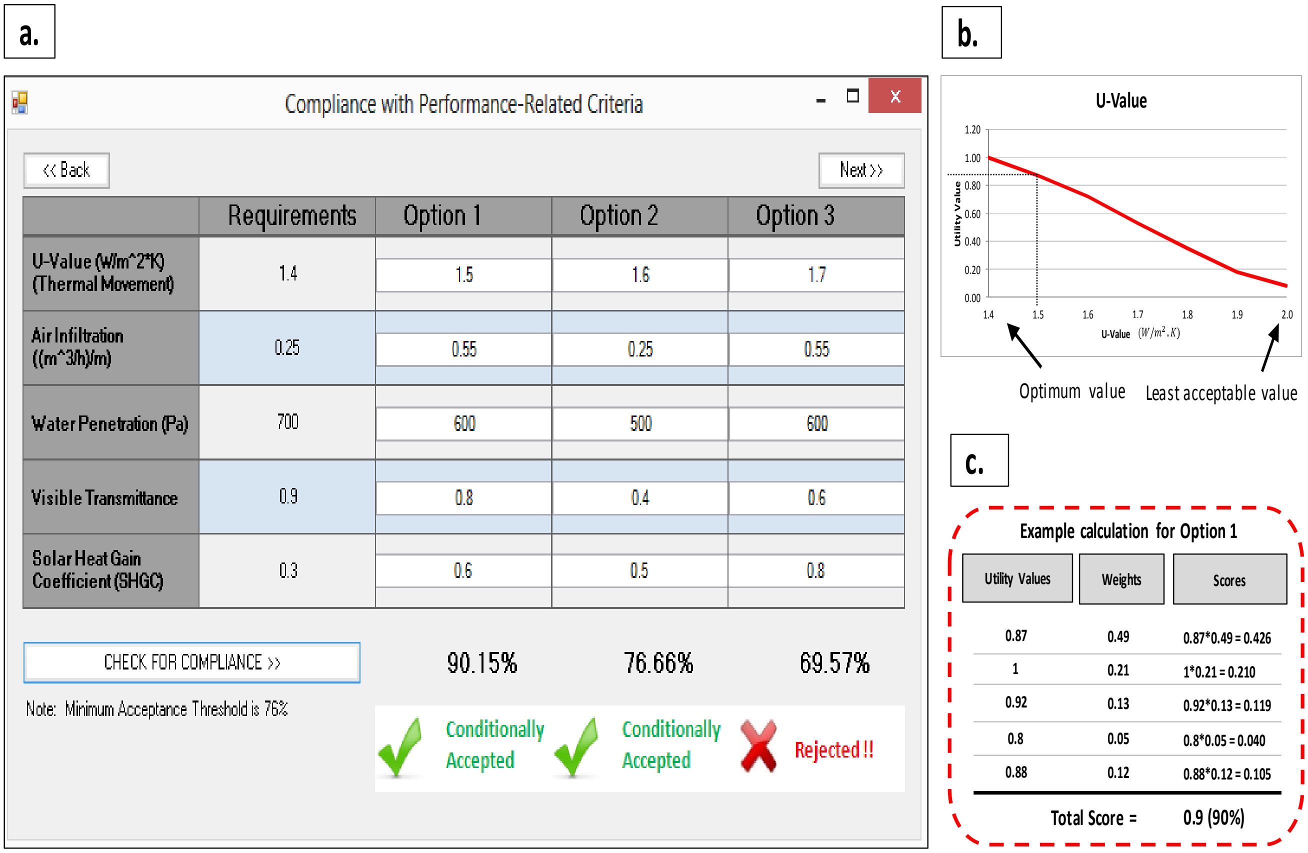

Fig. 7: Compliance check with performance criteria

As an example of using the performance criteria, Fig. 7b applies to Option 1 window (has a U-value of 1.5 W/m2°K), and thus receives a utility score of 0.87 (from the curve) for the U-Value criterion. Following this process for all five criteria, the total score for Option 1 is computed as the weighted sum of criteria scores by their weights (automated background calculation hidden from the user), as shown in Fig. 7c. The criteria weights were determined using AHP in the Setup phase. Using an acceptance overall performance threshold of 76%, Option 1 and Option 2 were determined to be conditionally accepted (borderline submittals) while Option 3 was rejected.

The two borderline submittals then proceeded to the “Impact Assessment” step. The construction implications were estimated based on the contractor’s input. Operational implication of changing the U-value can be computed as the additional cost of heating associated with a lower quality window.

Energy calculation thus depends on factors such as surface areas, heating degree-days (HDD), cooling degree-days (CDD), and the price of natural gas/electricity. Accordingly, the cost of energy consumption used for heating and cooling can be estimated based on Sherman [27], as follows:

$$E\_heating = 24 \div 1000\ (U \times A \times HDD)\ P\_gas \qquad (1)$$

Where:

Eheating is the yearly charges of energy consumption used for heating in dollars;

U is the U-value for building surface areas including walls, windows, and roof in W/m2°K;

A is total surface areas for walls, windows, and roof in m2;

HDD is the heating degree-days in °C-day (i.e. 3374 °C-day for Waterloo, ON); and

Pgas is the monthly price of natural gas in \$/kWh (assumed to be 0.022 Canadian cents).

$$E\_cooling = 24 \div 1000\ (U \times A \times CDD)\ P\_e \qquad (2)$$

Where:

Ecooling is the yearly charges of energy consumption used for heating in dollars;

U is the U-value for building surface areas including walls, windows, and roof in W/m2°K;

CDD is the cooling degree days in °C-day (i.e. 683 °C-day for Waterloo, ON); and

Pe is the monthly price of electricity in \$/kWh (assumed to be 0.09 Canadian cents).

Thus, the total cost of energy (Etotal) is the summation of Eheating and Ecooling. Table 2 illustrates sample energy calculations for the borderline submittals and also shows the amount of money that could be imposed to building operation over a specific period of time and interest: present worth. As shown in Table 2, the present value for changing the U-value from 1.4 W/m2°K to 1.5 W/m2°K is $6,250, over 10 years of operation and a 3% interest rate (Construction-related costs are assumed to be negligible in thi example).

A summary of the evaluation results is shown in the final report of Fig. 8, where Option 2 appears to cost more than Option 1 over the long term with costs of $12,501 and $6,250 respectively. Submitting an item with a U-value of 1.6 (Option 2), which is only a difference of 0.2, leads to approximately 10% extra energy consumption cost per year ($12,501 in 10 years). In this example, the proposed framework suggests that these two options could be acceptable but the project will need to be compensated with an amount equal to the extra energy cost: $6,250 for Option 1 or $12,501 for Option 2. The final report of Fig. 8 summarizes the information needed for negotiation and decision-making, including general information, and compliance results.

Table 2: Ten-year energy cost calculations

	As Specified	Borderline submittals	
		Option 1	Option 2
	U-value $(W/m^2.K)$	U-value $(W/m^2.K)$	U-value $(W/m^2.K)$
	0.21	0.21	0.21
	1.40	**1.50**	**1.60**
	0.40	0.40	0.40
Cost of *Heating* ($) eq. (1)	$7,028	$7,429	$7,830
Cost of *Cooling* ($) eq. (2)	$5,820	$6,152	$6,484
Annual Cost of Energy Consumption ($)	**$12,848**	**$13,581** 5.4% *difference*	**$14,313** 10.4% *difference*
Operational Cost ($) (10 years and 3% interst rate)	N / A	**$6,250**	**$12,501**

As shown, Option 1 scores better in performance (i.e., 90%) than Option 2. Option 2 imposes more implications in total but requires less maintenance work in the long run. Best value for the project should be selected by considering the output of the framework. In this case study, Option 1 was selected, as the project performance is critical and of priority. The framework is not intended to provide solid or exact decisions for specific scenarios. It rather reports all acceptable options and a sensitivity analyi report to allow the decision maker, contractor, and project manager to choose and negotiate the preferred option. The sensitivity analysis reports how the changes in the U-value, or other window parameters, affects the evaluation score and compensation amount. 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. Finally, upon the selection of an appropriate option, the approved submittal is updated in Revit to complete the "Reporting and Updating" step.

V. Comments and Future Exetensions

Upon developing the decision support framework, its prototype was tested on various submittal scenarios. The test scenarios were taken from the collected submittal logs with several assumptions made to compensate for missing design rationale information. The following comments and suggested improvements are made by the authors based on the results of experimenting with the framework on the case study and the feedback from the participating practitioners:

- Typically, mechanical and electrical systems are focused upon during design and submittal evaluation. However, certain architectural components (for example windows, as demonstrated in this study) can cause a significant effect on energy consumption and the overall performance of the building. Thus, these components require greater attention during design and submittal evaluation.
- Integration between the BIM platform (Revit Architecture) and the decision analysis tool required an extensive effort for programming and customization. Part of the challenge exists because the customization features are still basic and may not function properly for some versions of the BIM platform.
- While the proposed system is designed for the purpose of evaluating window submittals, its methodology is flexible, and thus has the potential to be easily adapted to include more architectural aspects or other items for further evaluation.
- In this study, the calculation method of energy consumption can consider the complex details of floors, partitions, ceiling, equipment, occupants, or air infiltration. These latter systems are needed to refine energy consumption calculation.
- Currently, an effort is being made to validate the system on real-life case studies.

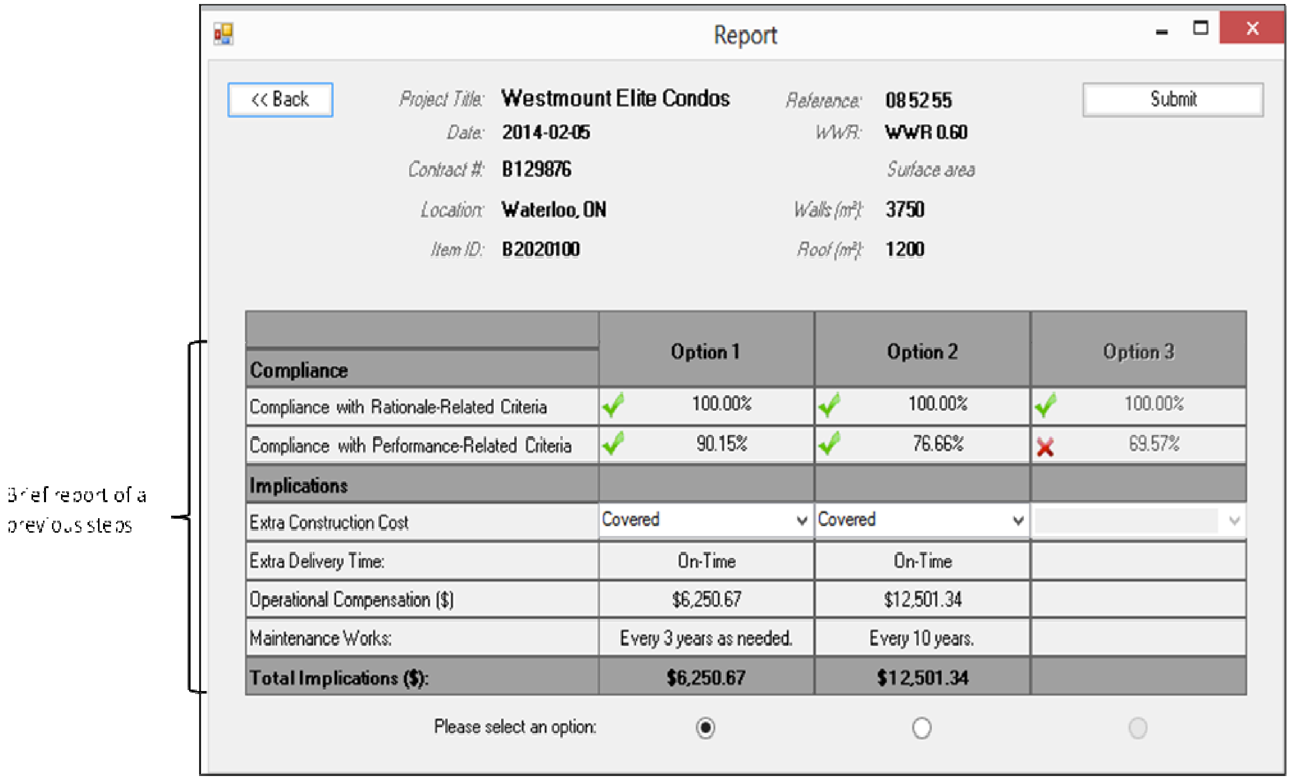

Fig. 8: Final report

VI. Conclusion

This paper developed a BIM-based DSS to help project managers make efficient decisions regarding the evaluation of critical architectural submittals. The proposed mechanism evaluates submittals considering design rationale, predefined performance criteria, and any construction or operational implications. The framework is designed to offer an on-the-spot decision mechanism for contractors and consultants by integrating BIM platform with a decision analysis application. The proposed system has shown potential in improving the capabilities of BIM to store rationale-related and performance-related criteria, update approved submittals, and facilitate better operation of buildings. Such a mechanism contributes to speedy evaluation, less disputes among all parties, and achieving best value for the project.

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