Exterior walls selection framework using Building Information Modeling (BIM)

Ammar M. Saud1, Khalid S. Al-Gahtani2, and Abdullah M. Alsugair1

Abstract: The building material selection among different options is a crucial issue affected by quality and cost. The implementation of the value engineering (VE) process is challenging. Thus, this paper proposes a framework for automating the VE process and integrating it with the decision-making process for building material selection. Moreover, this process becomes easily applicable by using Building Information Modelling (BIM). This study’s research methodology combines VE, Analytical Hierarchy Process (AHP), Pairwise, and Function Analysis System Technique (FAST) methods to select the best choice of eight assemblies of exterior walls based on nine identified criteria. Moreover, a questionnaire is used to validate the chosen criteria weights. Furthermore, a case study of a commercial building is conducted. Eight assemblies of exterior walls are modeled and evaluated using the proposed framework. Finally, the results are presented to three experts to receive their feedback, and it shows that the proposed framework gives a reliable evaluation of the value of each alternative. The programmed framework with BIM is a great aid to the decision-maker to select the most valuable materials during the design stage. This study gives guidance to future studies to standardize the external walls alternative to be evaluated more efficiently.

Subjects: Automation; Composite Materials; Sustainable Architecture; Building and Construction; Construction Materials

Keywords: Value engineering; BIM; quality; function analysis; life cycle cost; building; external wall; standards

ABOUT THE AUTHOR

Ammar Saud holds a Master’s degree in Construction Engineering and Management from King Saud University as well as a Master in Global BIM Management from Barcelona University. He focuses on the BIM field and its applications in improving the process of construction and design. Since 2011, he has been professionally and academically involved. https://engineering.ksu.edu.sa/en/CE

Dr. Khalid S. Al-Gahtani got his B.Sc. and Master’s degree in Civil Engineering from King Saud University (KSU). He received his Ph.D. degree from the State University of New York at Buffalo in Construction Engineering and Management. He is a professor for Civil Engineering at KSU. He served at several administrative and academic positions at KSU. His research interests in analyzing delay claims using the CPM schedule, Construction Automation including BIM application, Value engineering, Sustainability, and Risk Management. https://faculty.ksu.edu.sa/en/kgahtani

Dr. Abdullah M. Alsugair got his B.Sc degree in Civil Engineering from King Saud University (KSU), Saudi Arabia. He received his M.Sc degree from University of Colorado at Boulder, CO, USA, in Construction Engineering and Management. He received his Ph.D. degree from Texas A&M University, College Station, Texas, USA, in Construction Engineering and Management. He is a professor in Civil Engineering at KSU. He served at several administrative and academic positions at KSU among them Vice President for Projects. His research interests in Construction contract administration, Construction Automation including BIM application, Value engineering, Sustainability. https://faculty.ksu.edu.sa/en/amsugair
1. Introduction
The construction industry is one of the world’s leading industries used to measure a country’s economy (Dlamini, 2012). The appropriate selection of building materials and project complexity seriously affect the project’s cost (Cunningham, 2013). The National Association of Home Builders (NAHB) survey reported that the exterior wall finish cost 7.2% of the total construction cost (Taylor, 2014). Accordingly, there is a need for design engineers to be assured of its proposed design and its perfect choice.

Value engineering (VE) is a known method for improving building material selection. Three major issues are mostly addressed in VE. Quality, function, and cost are the three factors. To make the best and most valuable decision, the owner wants the highest quality of the performed function at the lowest possible cost. Dell’Isola (1997) defines the relation of these three factors in the following formula.

\[
\text{Value} = \frac{\text{Function} + \text{Quality}}{\text{Cost}}
\]  

The exterior wall is considered a significant building material that needs to be studied because of its impact on building value and energy consumption. Thus, this study uses exterior building walls as selected material to implement the proposed framework. The difference between the exterior building wall and other materials includes many layers that must be studied carefully. These exterior wall layers can be pre-manufactured and installed on the site or constructed directly. The exterior wall constitutes the cladding, enclosure structural components, and anchorage areas. Additionally, cladding can also have more than one layer, including the insulation layer (Alshamrani et al., 2017).

Because of the complexity of comparing different exterior walls, there is a need to have a systematic approach to automate these selection methods. Many international standards use a standard test to determine the quality of construction materials and set a minimum value of an agreed quality measurement unit. Some countries have their standard of material, such as Saudi Standards, Metrology, and Quality Organization (SASO), adopted from the international standard. These material standards can be used to create criteria for building material to be automated.

As a result, this study introduced a framework model to fully automate the material selection process for building exterior walls utilizing VE’s concept. A combination of VE, Analytical Hierarchy Process (AHP), Pairwise, and Function Analysis System Technique (FAST) approaches were employed in this study’s framework methodologies. The study defines nine external wall criteria based on international standards, research, and experts in this area. Measuring criteria quality varies from one country to another one. Hence, this study can be customized to a specific country like Saudi Arabia. Because most of the external walls are formed on the site, not in a factory such as the precast wall, this study defined eight common external walls used in Saudi Arabia. The study evaluated these external assembly walls based on experts’ judgments and standard tests. These eight assemblies are programmed with BIM to be easily used by the practitioners. The future of this study is to encourage more studies to standardize the composite of external walls to be recorded by the material factory and downloaded directly to the BIM model without manual entry. The framework was validated using a case study, questioners, and consulting number of experts of quality engineers.

2. Literature review
The selecting material has been broadly covered in writing through numerous methodologies (Crane et al., 1997). Besides, MCDM has been used as a research tool since 2000 (Ho et al., 2010). Because of its simplifying complex problems to the natural form has become a typical method for solving decision-making problems in many areas. One of the MCDM applications is material selection (Eltarabishi et al., 2020). Yazdani (2018) proposes two new multi-attribute
decision-making approaches that include applicability and performance of the design and material aspects. Also, Shahinur et al. (2017) study a model to select optimal materials with uncertainty.

2.1. Selection methods studies using AHP techniques
One of the methods of MCDM is the AHP technique. It is a known method that has been used for decision-making. The building and construction area use the AHP method to select construction materials and machines (Lin & Yang, 1996). It has three components. The first component is the ultimate goal or issue that needs to be addressed. The second one is all potential and called alternatives. The third component is the criteria that need to evaluate the alternatives. It selects the alternatives by determining these alternatives' priorities. These priorities are defined by specifying the goals or the importance of attributes hierarchically for each choice (Song & Kang, 2016).

2.2. Selection external walls studies
In areas of external walls and façades on the building, Mayhoub et al. (2019) proposed a technique to evaluate the alternatives of building façade materials considering their thermal performance and energy efficiency. Baglivo et al. (2014) determined a set of possible external wall configurations to choose the proper solution using a Pareto front of the multi-objective problem. Using the AHP method, Nadoushani et al. (2017) developed a systematic method for selecting a façade system by considering social, economic, and environmental criteria. However, there is a need to consider both the energy and Life Cycle Cost (LCC) when performing the life cycle analysis. Alshamrani et al. (2017) present a study selecting exterior wall materials according to their LCC. Carvalho et al. (2021) developed a BIM-based decision-making tool for designers to evaluate the environmental, economic, and functional performance of 18 different combinations of external walls, roofs, and floors using Dynamo during the project's early stages. Zhang et al. (2021) proposed a multi-criteria decision-making framework for selecting external wall retrofit schemes in buildings using BIM. Bapat et al. (2021) developed a methodology by applying the fuzzy factor comparison method to choose the most feasible and sustainable material. This methodology, automated by BIM, aids in designing the floors, ceilings, walls, cladding, openings, and fenestrations for an infrastructure transportation facility. Thus, there is an urge to systematically consider the VE concept that includes quality, function, and LCC from previous studies.

2.3. Selection material studies by using BIM
In academic research, many studies used BIM integration with other systems to automate the selection process (Fazeli et al., 2019; Jacoski & Hoffmeister, 2018; Jalilzadehazhari et al., 2019; Kamari et al., 2018; Khanzadi et al., 2019; Ma et al., 2019; Najjar et al., 2019; Nwodo et al., 2018). Growing research attention used BIM to facilitate the material selection process in selecting building material areas. To optimize the sustainable building components selection, Fazeli et al. (2019) proposed integrating BIM with decision-making and problem-solving approaches containing Fuzzy and TOPSIS. Khanzadi et al. (2019) developed an automated framework for selecting the best available building components that consider sustainability aspects in the BIM environment. Ma et al. (2019) integrated BIM with green material characteristics in coastal buildings for evaluation purposes. Nwodo et al. (2018) proposed a framework for integrating a decision support system (DSS) for materials selection into BIM for cost, energy, carbon, and mechanical strength. Najjar et al. (2019) used BIM integration to evaluate the construction materials' lifecycle and estimate buildings' overall lifecycle energy use. To exchange information between the designer and the owner about material values, Jacoski and Hoffmeister (2018) proposed a method for updating and retrieving the BIM object's values. Kamari et al. (2018) integrate BIM to create comprehensive redesign situations during the early design stages. Jalilzadehazhari et al. (2019) incorporate BIM, the design of experiments as an optimization algorithm, and AHP into an MCDM method.

3. Research methodology
The proposed methodology in this study consists of three phases, as shown in Figure 1. The first phase is concerned with developing the framework for selecting an external wall. It consists of six steps, including integrating the framework with the BIM modeling. Phase 2 is applying the framework with a case study. The final phase is to validate the case study results with experts.
3.1. **Phase 1: Develop the framework of selecting external wall systems for buildings**

Figure 1 shows the framework of the material selection process. The framework process consists of six steps. It starts with defining the material evaluation criteria with considering material function. The next step is to evaluate the Criteria Weight (CW) based on function analysis for each material criterion. After that, the Quality Weight (QW) for each material is calculated based on the summation of Criteria Quality Weight (CQW) evaluated based on the agreed measurement unit and multiplied by the CW according to the AHP method.

Besides defining material evaluation criteria, material LCC needs to be estimated. Finally, the value score (V) was calculated by dividing the QW by the LCC for each material alternative.
3.1.1. Step 1: Choosing the predominant criteria
The predominate external walls criteria are established following the below sequential four tasks.

3.1.1.1. Task 1: Collecting the information sources of the external wall systems criteria. This step focuses on establishing the essential evaluation criteria for the selected material. In general, this task in our study is achieved by following three methods. The first method is to search the literature review and group all these criteria into appropriate items (Nwodo et al., 2018). The second method is studying the international material standard that usually follows a standard test to measure the quality criteria (Heaton et al., 2019). Usually, these standard tests recommend minimum measured items to allow acceptance of this material. The purpose of these standards is to preserve safety and health, as well as to measure, analyze, manage quality, and protect the environment (Grob, 2003). These standards are excellent for achieving this task because of their high reliability and quantitative measurement. A third method uses statistical method tools by using questionnaires, interviewing, workshops, and other means to document the opinion of criteria materials from experts, scholars, and practitioners (Lin & Yang, 1996). Several papers studied the wall criteria (Baglivo et al., 2014; Boostani & Hančer, 2018; Iribarren et al., 2015; Marzouk et al., 2013). The interest of these studies is to select material based on environmental perspective and energy use. Al-Hammad et al. (2014) studied the criteria from the perspective of material quality, specified a well-studied list of criteria, and used a statistical method to validate it. In this study, the Saudi Standards, Metrology, and Quality Organization (SASO, 2022) defined the quality criteria with measurement tests. Furthermore, the study interviewed three experts from quality engineering in a material factory that acknowledges the material quality tests. Those experts’ opinions are highly weighted because of their reliability and knowledge of the technical aspect.

3.1.1.2. Task 2: Eliminate the unrelated criteria. As a result of studying the different quality criteria methods, this study reaches a nine list of quality criteria after studying a long list of criteria. Table 1 specifies these quality criteria items associated with a measuring unit of the standard test. Three of these criteria have a subjective measurement that needs to be defined by the building designer or project stockholders.

3.1.1.3. Task 3—Setting measurement unit of the external wall criteria. The previously identified nine criteria are required to be measured. There are two types of criteria measurement. One of them is subjective, and the other one objective. Table 1 shows the identified measurement units for each criterion according to three expert interviews. Criteria 1 to 6 are identified based on a standard test (objective value), while criteria 7 to 9 do not have a standardized test (subjective value). All these nine criteria, objective and subjective, are necessary to be weighted, as discussed later in step 3.

3.1.1.4. Task 4: Verify the selected external wall criteria. A questionnaire that seeks the opinions of professional engineers/architects who work in Saudi Arabia has been done to increase the validation of generating the nine criteria. The question was which of the listed criteria influence the quality of exterior walls material. 1078 persons received the questionnaire. The respondents were 106 persons (9.83% of the total receivers), with 8.5% of the respondents were with a Ph.D. degree, and 29.2% were with a master’s degree. 61.3% had a bachelor’s degree. The respondents’ backgrounds were mainly Civil Engineering (65.1%) and Architecture (19.8%). They have experience in various areas, Contractors (37.7%), Consultants (17.9%), Designers (10.4%), Client Representatives (9.4%), Academic Researchers (9.4%), and others. The results showed that all criteria were agreed to by more than 25% of the respondents. Figure 2 summarizes the major, specialization areas, education level, and years of experience of 106 survey respondents.

3.1.2. Step 2: CW evaluation
VE concept uses function analysis to select material besides the quality criteria. One popular method to assess the material function is the FAST technique (Dell’Isola, 1997).
representation, this final output technique determines the logical linkages between the functions of the material or project. The approach, on the other hand, does not compute the weight of each function item. On the other side, the AHP, which adopts the pairwise weighting method, is a known selection method. However, the method does not include functional analysis in their procedure (Bhushan & Rai, 2004; Zardari et al., 2015). Lin and Yang (1996), Liu and Hai (2005), and Hamdan and Cheaitou (2017) use the hierarchy analysis chart in their analysis for the selection process without the inclusion of functional analysis. This study’s added value is integrating the FAST and AHP method for defining the CW for all material criteria selection.

The purpose of CW used in the AHP method is to determine how each criterion is essential to relate it to other criteria (criteria priority; Song & Kang, 2016). In our study, the CW is defined by FAST analysis to meet the project goal. Zardari et al. (2015) emphasized that many researchers
Figure 2. Caption: The respondents of the questionnaire analysis.

| Major | Specialization Area |
|-------|---------------------|
|       | Civil Engineering   | 19.9%  |
|       | Architecture        | 19.9%  |
|       | Electrical Engineering | 19.9% |
|       | Operation manager   | 19.9%  |
|       | Surveying           | 19.9%  |
|       | Chemistry           | 19.9%  |
|       | Interior Design     | 19.9%  |
|       | Construction engineering and proj. | 19.9% |
|       | Designer             | 9.4%   |
|       | Contractor           | 9.4%   |
|       | Consultant           | 17.9%  |
|       | Client Representative | 38.7% | |
|       | Supplier             | 50.4%  |
|       | Academic Researcher  | 17.9%  |
|       | Student              | 13.2%  |
|       | Environmental specialist | 13.2% |

| Education Level | Years of Experience |
|-----------------|---------------------|
| Bachelor        | 42.5%               |
| Master          | 26.4%               |
| Ph.D            | 13.2%               |
| Diploma         | 17.9%               |
| 1-5             | 17.9%               |
| 6-10            | 17.9%               |
| 11-15           | 17.9%               |
| more than 15    | 17.9%               |

overlook the difficulties of estimating CWs. They assume the decision-makers are aware of the criteria evaluation. The following four tasks can be used to calculate CW in this framework:

3.1.2.1. Task 1: Establishing the project’s AIM and conducting a function analysis. The materials chosen must achieve the project’s main goal. As a result, at the early stages of the project, the owner and design team must establish the principal purpose and functions. Goals are necessary for understanding the “what” and “why” of design. In the VE process, function analysis also plays an important role. The material criterion cannot be accurately weighed if the function analysis is not properly determined. For instance, the weight of the esthetical criterion for a hotel structure is higher than for a warehouse. As a result, it would be preferable to choose a more aesthetic material. Thus, it would be preferred to select the material of a more esthetical rank (Dell’Isola, 1997).

3.1.2.2. Task 2: Link the criteria with its function/subfunction/criteria. This phase applies an integration between the FAST and AHP/Pairwise method. Each criterion must be relevant to its respective function to accomplish this integration. Figure 3 shows how the criteria are linked with this study’s material function. The left side of the chart (rectangular shape) represents the function analysis from the FAST method, and the right part (oval shape) represents the material criteria resultant from step 1. The project designer expert determines the function analysis and criteria distribution. A brainstorming session between the authors and three professional design engineers was conducted to achieve this task. Accordingly, the goals that lead the enclosure design included in the building design goals broke down into performance, organizational, visual, and cost goals, as Boswell (2013) mentioned.

Moreover, project location, local climate, and geography are considered in the functional analyses. Figure 3 shows the final results of these functions and subfunction distribution. Besides, in the same brainstorming session, the client and design team assigned appropriate criteria to its relevant function. Notice in this figure that the material criteria are represented by an oval shape and linked to function/subfunctions represented by a rectangular shape.

3.1.2.3. Task 3: calculation of Distributed Criteria Weight (DCW). As shown in Figure 3, some criteria may be assigned to more than one function. As a result, all criteria must be weighed and evaluated using one of the two methods below. If the compared criteria in one level are
fewer than or equal to three, the point allocation method is used, according to Zardari et al. (2015). In the point allocation method, the decision-maker allocates numbers to describe the criteria weights directly. If the compared criteria at one level are more than three, the pairwise comparisons method is adopted. Using scale factors ranging from 1 to 9, the pairwise comparison approach uses expert judgment to assess the relative value of each of the criteria against each other. Each has one if the two criteria are equally important. If one criterion is more significant than the other, a factor of importance degree is assigned on a scale of 2 to 9. Then the method developed a matrix and used equations to reach the weight for each criterion as described by Bhushan and Rai (2004).

The weights are given at each level of the FAST diagram. The pairwise comparison has been used to compare the secondary functions (Resist Threats, Improve The Environment, Attract Customers, Facilitate The Operation) as per the matrix shown in Table 2. Other weights are given by the point allocation method by using the same experts on the previous step (Figure 3). The first three
columns in Table 3 show all the linked paths from function/Subfunction/Criteria of the FAST chart of Figure 3.

After assigning weights for all the functions and subfunctions on FAST Diagram, the next task is to determine the weight for each criterion linked with function and subfunction. This task can be done by multiplying all weights of each path of the FAST diagram. As shown in Figure 3, each path might have function, subfunction, and criterion. Equation 2 shows the calculation of DCW (Song & Kang, 2016):

\[ DCW_i = \sum_{j=1}^{\text{number of paths}} W_{\text{function}} \times W_{\text{subfunction}} \times W_{\text{criteria}} \]  

(2)

Based on this arrangement, Distributed Criteria Weight (DCW) is calculated for each criterion for each linked function by multiplying its weight by all the weights in the same series/paths in the hierarchy in Figure 3. The last four columns in Table 3 represent the weight of function, subfunction, criteria, and the DCW. Notice that all DCW equals one (equivalent to 100%), which verified the calculation.

3.1.2.4. Task 4: calculation of CW for each criterion. The DCW for all material requirements will be assigned as a result of the previous four phases being implemented. Because material criteria might be linked to several functions/subfunctions, CW for each criterion should be calculated by summing all DCW that are related to that criterion, as formulated by the equation:

\[ CW_i = \sum_{j=1}^{\text{number of DCW}} (DCW_j) \]  

(3)

For getting the Nine CW’s of the exterior wall from Table 3, all the DCW related to more than one function/subfunction summed in one item are represented in Table 4. For example, Thermal Insulation criteria are under three functions (Resist Threats, Improve the Environment, and Facilitate The Operation). Thus, its CW equals 0.02 + 0.18 + 0.11 = 0.31, as shown in Table 4, representing the summation of all DCW related to thermal insulation criteria. Accordingly, Table 4 represents the CW for all Exterior Wall criteria following such calculation.

All CW for the overall material should be equal to 1 (equivalent to 100%) to validate these calculations.

As noticed, CW of criterion 3 is zero, which means that this creation is not a factor in selecting an external wall based on expert view for a commercial building in Saudi Arabia, Riyadh city. These CW’s are evaluated based on a typical external wall condition, including constructing a new

| Table 2. The pairwise comparison matrix |
|----------------------------------------|
|                                        |
| **Resist Threats** | **Improve the Environment** | **Attract Customers** | **Facilitate the Operation** | **w vector** |
|---------------------|-------------------------------|-----------------------|-------------------------------|--------------|
| Resist Threats      | 1.00                          | 0.20                  | 0.33                          | 0.33         | 0.09         |
| Improve the Environment | 5.00                      | 1.00                  | 1.00                          | 0.33         | 0.26         |
| Attract Customers   | 3.00                          | 1.00                  | 1.00                          | 1.00         | 0.28         |
| Facilitate the Operation | 3.00                      | 3.00                  | 1.00                          | 1.00         | 0.38         |
| 12.00               | 5.20                          | 3.33                  | 2.67                          |              |             |
Table 3. Calculation of the DCW for each function/subfunction/criteria path

| 1- Function          | 2- Sub-Function          | 3- Criteria             | W1  | W2  | W3  | DCW = W1*W2*W3 |
|----------------------|--------------------------|-------------------------|-----|-----|-----|----------------|
| Resist Threats       | Resist Weather Elements  | Wind Load Resistance    | 0.09| 0.60| 0.30| 0.02           |
| Resist Threats       | Resist Weather Elements  | Thermal Insulation      | 0.09| 0.60| 0.30| 0.02           |
| Resist Threats       | Resist Weather Elements  | Water Resistance        | 0.09| 0.60| 0.40| 0.02           |
| Resist Threats       | Resist Fire              | Fire Resistance         | 0.09| 0.20| 1.00| 0.02           |
| Resist Threats       | Resist Applied Loads     | Wind Load Resistance    | 0.09| 0.20| 0.80| 0.01           |
| Resist Threats       | Resist Applied Loads     | Weight                  | 0.09| 0.20| 0.20| 0.00           |
| Improve the Environment | Air Conditioning      | Thermal Insulation      | 0.26| 0.70| 1.00| 0.18           |
| Improve the Environment | Reduce Noisily          | Sound Transmission      | 0.26| 0.30| 1.00| 0.08           |
| Attract Customers    | Improve Appearance       | Aesthetic               | 0.28| 1.00| 1.00| 0.28           |
| Facilitate the Operation | Thermal Insulation   |                          | 0.38| 1.00| 0.30| 0.11           |
| Facilitate the Operation | Durability              |                          | 0.38| 1.00| 0.30| 0.11           |

\[ \sum W = 1 \]

Alt Text: Calculation weight of function, subfunction, criteria, and the DCW. Notice that all DCW equals one (equivalent to 100%). The first three columns show all the linked paths from function/ subfunction/criteria of the FAST chart of Figure 3.
building, low elevation building, typical weather, reasonable noise area, and flexible cladding options selection. However, in the case of renovation of the existing building, the weight criteria could be a significant factor for safety. Also, Criteria 4 (sound Transmission) could be high weight in locating the building near a noisy area. The Water Penetration Resistance criteria would be more critical in the building located in the humidity area (Loganina, 2020). For the Thermal Insulation, criteria can be more weight in the area's location having extreme weather (D’Agostino et al., 2019). Heidari Matin and Eydgahi (2021) studied different facade angle movements with hourly daylight patterns for minimizing heat loss. Also, Bajno et al. (2020) studied the effect of thermal and moisture in the external historical wall. In addition, Wind Resistance would be meaningful in the case of high rising buildings. Finally, the Aesthetic criteria would be an influential factor in following a particular faced theme by government regulations to preserve the country's heritage. As an extension of this study, there is a need to develop a more typical CW for each or combination of the four furthest building conditions:

(1) having critical building structure;
(2) extreme weather area;
(3) needing quiet area inside the building and;
(4) having a high elevated windy building;
(5) having restrictions on building faced.

The purpose of these development weights is to standardize the exterior wall CW to be programmed with BIM and gives good quick results.

3.1.3. Step 3: QW calculation
After defining the criteria items and defining the CW, there is a need to define the material QW. This calculation can be done through three tasks. Task 1 defined the CQW for each criterion and normalized these CQW in Task 2 of this step. Finally, calculate the QW for each material alternative in Task 3.

3.1.3.1. Task 1—calculate the CQW. As mentioned in step 1, each criterion needs to be measured according to international tests, especially Saudi standards (SASO 2022) in this study. Other sources include manufacturer’s information, manuals, material catalogs, information available from contractors, specialized consultants, and other literature (CSI, 2011), as indicated in Table 1. Thus, each criterion quality needs to be weighted according to the material data and specifications. These measured agreed tests require to be applied to different materials. These

| Weights Parameters               | Criteria Weights (CW) |
|----------------------------------|-----------------------|
| WP.01. Wind_Load_Resistance      | 0.03                  |
| WP.02. Thermal_Insulation        | 0.31                  |
| WP.03. Weight                   | 0.00                  |
| WP.04. Sound_Transmission       | 0.08                  |
| WP.05. Fire_Resistance          | 0.02                  |
| WP.06. Water_Penetration_Resiste| 0.02                  |
| WP.07. Aesthetic                | 0.28                  |
| WP.08. Durability               | 0.11                  |
| WP.09. Maintainability          | 0.15                  |
| Σ WP                            | 1.00                  |

Alt TEXT: Calculation of CWs values for exterior wall from Table 3. All CW for the overall material should be equal to 1 (equivalent to 100%).
materials range from low quality to high one to define the material quality classification. If the criterion is not measured, the design professional will weigh the CQW subjectively according to his/her experience. A 1–5 scale is utilized, with 5 representing excellent and 1 representing bad.

The exterior wall is a particular building material type since it is a composite from different layer material that requires to be measured by its identified criteria. The exterior wall assembly consists of the cladding, enclosure structural components, anchorage areas, and insulation. Furthermore, these layers have a list of combinations and require measurement. Three professional designers selected eight exterior wall alternatives commonly used in Saudi buildings to control these varieties. The team selected the alternative to be more diverse and have a range of quality types, to be more generated to other external walls composite and a base to measure them. Table 5 shows the details of the eight alternatives of wall assemblies.

The three subjective criteria of the eight exterior wall alternatives are weighted according to professional design expertise. An expert engineer estimates the qualitative criteria of wind load resistance, water penetration, and fire resistance. Therefore, these CQW values were estimated according to the expert team based on their experience. Table 6 shows the CQW for all exterior walls and the measurement unit for each criterion test.

At the end of this task, any new material's QW within these eight assembly alternatives can be evaluated. Other external wall assembly alternatives can be compared with these eight alternatives to estimate its standard test measurement weight and quantify its quality classification.

### 3.1.3.2. Task 2—Normalize the CQW. To use the CQW to calculate QW, these tests must first be normalized to be scaled from 0 to 1. For each material alternative, the sum of all CQW should be weighted to one (equivalent to 100 percent). It’s easier to interpret and measure CQW after it’s been normalized. Linear Scale Transformation, Max Method (LSTMM) is one method for normalizing a value (Nirmal & Bhatt, 2016). In this study, the following equation is used to normalized quality and LCC:

\[
R_{ij} = \frac{X_{ij}}{X_{iMax}}
\]

Whereas:

- \(R_{ij}\): Normalized value of material i for criterion j
- \(X_{ij}\): Criterion value of the evaluated material
- \(X_{iMax}\): Maximum criterion value

Because each CQW has a range of measurement values, it requires normalizing these units to simplify the criteria weight value. The normalized rank matrix in Table 6 is generated using equation 4. For example, the Fire Resistance criterion quality value in Table 6 ranged from 1.6 to 4 hours. Table 6 shows the value of 4 hours as 1 and 1.6 as 0.4 (i.e., 1.6 divided by 4).

### 3.1.3.3. Task 3—calculate the QW. Before moving on to the next phase, each material’s ultimate quality value (QW) must be calculated from the CQW determined before. This new QW factor is calculated by multiplying each material criterion’s corresponding CW and CQW according to the following equation:

\[
\text{Quality Weight for each material } (QW_i) = \sum CQW_{ij} \times CW_i
\]

\(i = 1\) to Number of Criteria
Table 5. External wall assemblies’ alternatives

| Wall Assembly Number | First Layer | Second Layer | Third Layer | Fourth Layer | External Layer | Total Thickness (cm) |
|---------------------|-------------|--------------|-------------|--------------|-----------------|---------------------|
| Assembly 1          | -           | -            | Insulated concrete block 20 cm | Plaster 2.5 cm | Exterior Paint 0.1 cm | 22.6                |
| Assembly 2          | hollow core concrete block 10 cm | expanded polystyrene (EPS) foam board 5 cm | hollow core concrete block 10 cm | Plaster 2.5 cm | Exterior Paint 0.1 cm | 27.6                |
| Assembly 3          | hollow core concrete block 15 cm | Adhesive Styrofix 0.5 cm | expanded polystyrene (EPS) foam board 5 cm | Adhesive Mishfix 1 cm | Exterior Paint 0.1 cm | 21.6                |
| Assembly 4          | hollow core concrete block 10 cm | expanded polystyrene (EPS) foam board 5 cm | hollow core concrete block 10 cm | Subframe 5 cm | ACP 0.4 cm | 30.4                |
| Assembly 5          | hollow core concrete block 10 cm | expanded polystyrene (EPS) foam board 5 cm | hollow core concrete block 10 cm | Subframe 5 cm | A2ACP 0.4 cm | 30.4                |
| Assembly 6          | hollow core concrete block 10 cm | expanded polystyrene (EPS) foam board 5 cm | solid concrete block 15 cm | Anchorage 2 cm | Riyadh Stone 4 cm | 36.0                |
| Assembly 7          | hollow core concrete block 10 cm | expanded polystyrene (EPS) foam board 5 cm | solid concrete block 15 cm | Anchorage 2 cm | Granite 2 cm | 34.0                |
| Assembly 8 (Precast)| -           | -            | Concrete 7.5 cm | (EPS) foam board 5 cm | Exposed aggregate concrete 7.5 cm | 20.0                |

Alt TEXT: External wall assemblies' alternatives commonly used in Saudi buildings and used in this study. These alternatives are identified based on three professional designers.

j = 1 to Number of Material Alternatives

Therefore, all the CQWs of material alternatives in Table 6 are multiplied by corresponding CWs in Table 4. Then the results summed to get the QW for each material alternative according to the AHP method. The second column of Table 7 shows QW results for all the eight exterior wall alternatives. Below is a sample of these calculations for QW Alternative 1, 2, and 3:

\[
\text{QW (Alternative1)} = (0.03 \times 1.00) + (0.31 \times 0.82) + \ldots + (0.15 \times 0.44) = 0.75
\]

\[
\text{QW (Alternative1)} = (0.03 \times 1.00) + (0.31 \times 0.82) + \ldots + (0.15 \times 0.44) = 0.75
\]

\[
\text{QW (Alternative1)} = (0.03 \times 1.00) + (0.31 \times 0.82) + \ldots + (0.15 \times 0.44) = 0.75
\]

In order to validate the QW determined by the professional designer teams, another statistical method is used to determine the QW more promptly. Table 8 shows the QW generated by questionnaire respondents for the criteria importance. Table 7 represents the comparison between
| Criteria                      | Unit | Max. Wind Pressure (KN/m²) | R-value (m²K/W) | Fire Resistance | Water Penetration Pressure (Pa) | Sound Transmission | Fire Rate (hr) | Water Penetration | Fire Rate (hr) | Sound Transmission |
|------------------------------|------|-----------------------------|-----------------|----------------|---------------------------------|--------------------|----------------|-------------------|----------------|--------------------|
| Weight                       | Kg/m² | 0.00                        | 0.00            | 0.00           | 0.00                            | 0.00               | 0.00          | 0.00              | 0.00           | 0.00               |
| Normalized                   |      | 0.00                        | 0.00            | 0.00           | 0.00                            | 0.00               | 0.00          | 0.00              | 0.00           | 0.00               |
| Assembly 1                   | Weight | 2.90                       | 1.62            | 281            | 0.37                            | 4.5                | 4              | 0.80              | 4              | 0.80               |
| Normalized                   |      | 0.00                        | 0.00            | 0.00           | 0.00                            | 0.00               | 0.00          | 0.00              | 0.00           | 0.00               |
| Assembly 2                   | Weight | 2.90                       | 1.68            | 286            | 0.36                            | 4.2                | 4              | 0.80              | 4              | 0.80               |
| Normalized                   |      | 0.00                        | 0.00            | 0.00           | 0.00                            | 0.00               | 0.00          | 0.00              | 0.00           | 0.00               |
| Assembly 3                   | Weight | 2.90                       | 1.70            | 219            | 0.54                            | 4.6                | 4              | 0.80              | 4              | 0.80               |
| Normalized                   |      | 0.00                        | 0.00            | 0.00           | 0.00                            | 0.00               | 0.00          | 0.00              | 0.00           | 0.00               |
| Assembly 4                   | Weight | 2.90                       | 1.86            | 281            | 0.57                            | 5.8                | 4              | 0.80              | 4              | 0.80               |
| Normalized                   |      | 0.00                        | 0.00            | 0.00           | 0.00                            | 0.00               | 0.00          | 0.00              | 0.00           | 0.00               |
| Assembly 5                   | Weight | 2.90                       | 1.86            | 283            | 0.57                            | 5.8                | 4              | 0.80              | 4              | 0.80               |
| Normalized                   |      | 0.00                        | 0.00            | 0.00           | 0.00                            | 0.00               | 0.00          | 0.00              | 0.00           | 0.00               |
| Assembly 6                   | Weight | 2.90                       | 1.86            | 281            | 0.57                            | 5.8                | 4              | 0.80              | 4              | 0.80               |
| Normalized                   |      | 0.00                        | 0.00            | 0.00           | 0.00                            | 0.00               | 0.00          | 0.00              | 0.00           | 0.00               |
| Assembly 7                   | Weight | 2.90                       | 1.86            | 281            | 0.57                            | 5.8                | 4              | 0.80              | 4              | 0.80               |
| Normalized                   |      | 0.00                        | 0.00            | 0.00           | 0.00                            | 0.00               | 0.00          | 0.00              | 0.00           | 0.00               |
| Assembly 8                   | Weight | 2.90                       | 1.86            | 281            | 0.57                            | 5.8                | 4              | 0.80              | 4              | 0.80               |
| Normalized                   |      | 0.00                        | 0.00            | 0.00           | 0.00                            | 0.00               | 0.00          | 0.00              | 0.00           | 0.00               |

All TEXT: The CQW (weight and normalized) for all exterior walls and the measurement unit for each criterion test.
the results of the two methods. As shown in Table 8, the quality varies between the two methods. The difference between the same assemblies in each method is ranged from 1% to 14% within an acceptable level. The expert studying results are followed in this study as they are more reliable than the statistical method that asks respondents from different backgrounds. Additionally, the statistical method does not consider the project goal and functions.

3.1.4. Step 4: LCC estimation

LCC needs to be evaluated for each material alternative using the V of the selected material. LCC considers the material’s salvage value at the end of the building’s expected life cycle span, as well as the initial cost, operating, and maintenance costs. Many variable factors might alter the LCC, making it difficult to determine the exact equation. As is mentioned in the literature review section, many statistical approaches were applied to determine the material LCC. Other methods for evaluating LCC use index cost to give a quick estimate. At the end of this step, there is a requirement to normalize the LCC to be used on the next step, as explained previously, by using equation 4 and the maximum criterion value since all criteria follow ascending quality value.

3.1.5. Step 5: \textit{V Calculate and select the best options}

The best material option should have the highest quality score and the lowest lifecycle cost. According to Dell’Isola (1997), the last two steps have the requisite two variables to determine the V as in the following equation:

\[ V = \frac{QW}{LCC} \]  \hspace{1cm} (6)

\( V \) = Material Alternative Value.

\( QW \) = Normalized material Quality Weight

\( LCC \) = Normalized material Life Cycle Cost.

According to the VE concept, each material alternative gets its V. The preferred material alternative will be the highest total V by applying this equation for all material alternatives.

3.1.6. Step 6: \textit{Integrate the proposed framework with BIM}

Visual programming incorporates all investigated material types with their properties and criteria values in the BIM model. After selecting the material type, the CW, QW, and the quantity, the LCC will be instantly calculated. This task will facilitate the decision-maker to immediately observe the effect of their choices.

| Table 7. Comparison of the two weighting methods |
|-----------------|-----------------|-----------------|-----------------|
|                | QW, according to the | QW, according to the | Difference (±%) |
|                | expert judging      | Statistical weighting |                  |
| Assembly 1    | 0.75              | 0.79              | 5%               |
| Assembly 2    | 0.75              | 0.79              | 5%               |
| Assembly 3    | 0.80              | 0.84              | 5%               |
| Assembly 4    | 0.89              | 0.79              | -13%             |
| Assembly 5    | 0.90              | 0.82              | -1%              |
| Assembly 6    | 0.90              | 0.86              | -5%              |
| Assembly 7    | 0.91              | 0.86              | -6%              |
| Assembly 8    | 0.76              | 0.88              | 14%              |

Alt Text: Comparing the QW by using two weighting methods for validation.
Table 8. QW according to statistical weighting method

| Criteria                          | Respondents | Weight |
|----------------------------------|-------------|--------|
| Wind Load Resistance             | 38          | 0.08   |
| Thermal Insulation               | 83          | 0.18   |
| Weight                           | 29          | 0.06   |
| Sound Transmission               | 40          | 0.09   |
| Fire Resistance                  | 54          | 0.12   |
| Water Penetration Resistance     | 55          | 0.12   |
| Aesthetic                        | 42          | 0.09   |
| Durability                       | 64          | 0.14   |
| Maintainability                  | 46          | 0.10   |
| Σ R = 451                       | Σ WP = 1.00 |

Alt TEXT: QW according to statistical weighting method information.

In this research, Autodesk Revit software is adopted as a BIM Platform. Furthermore, Dynamo's visual programming is utilized to automate the needed steps of linking the evaluation process with the BIM model. The Revit API is provided by Dynamo, an open-source visual programming tool (Application Programming Interface). It allows users to graphically design programs by managing graphic elements known as “nodes.” It also allows you to access BIM data, write, modify, and automate repetitive processes.

Furthermore, Dynamo allows entering programming codes using the python language. It is usually used when more sophisticated programming is required. A python is a powerful programming language that can extend the capabilities of Dynamo. Figure 4 shows a sample of the system programming.

3.2. Phase 2: A case study of selecting exterior walls material
A commercial building case study will be studied in this paper to implement the framework's evaluation process for exterior walls and validate it. This case study will introduce and evaluate eight assemblies of exterior wall elements using the proposed framework. The results and output will be outlined to help the decision-maker select the material type that secures the best value.

3.2.1. Project description of the case study
The building is an exhibit located in Riyadh, Saudi Arabia's capital, in the an-Nafud desert with long, sweltering summers. Hence, engineers are concerned with buildings' air conditioning and thermal insulation. The building's objective is to allow customers to preview many building tiles and sanitary accessories. The structure is made up of a ground level (160 m²) and an 80 m² mezzanine. The ground floor is for the materials exhibit, and the mezzanine is for employees' offices. The project life cycle is assumed to be 30 years.

3.2.2. BIM modeling process
The eight-assembly external wall of the proposed framework was modeled within Revit software following the subsequent steps:

1. The external walls of the building are initially modeled with a Low Level of Development (LOD). According to the BIM Forum specification, it is equal to LOD 200 (BIMForum, 2021). Each external wall is shown as a single layer in this phase.
2. The eight wall assemblies are modeled as Revit types with LOD 300, showing the details of each layer’s material and thickness. Figure 5 Revit software represents the screenshot of these eight wall assemblies. Then, Dynamo adds all the criteria information to the wall types.
(3) After selecting the best alternative with the highest value, the external wall elements of the building are developed to LOD 300 using the types created in the previous step.

3.2.3. Applying the proposed framework on exterior walls case study

In this section, the proposed framework procedure illustrated previously will select the most valued material between the exterior wall's assembly alternatives through sequences steps. The framework in Table 7 is defined the QW for the eight assembly alternatives external wall. Now, the LCC will be estimated in the case study in task 1. Following task 2, the V for each of the nine alternatives will be determined, and the best alternative value is selected using the BIM model.

3.2.3.1. Step 1: Evaluate the LCC of selected material of the case study. The LCC depends on three factors: initial cost, maintenance cost, and salvage value cost (the exterior wall value at the end of the lifetime). Factories or contractors requested the initial and maintenance cost per material unit. The initial cost should include material and installation costs. In this study, the initial cost and Maintenance and Repair (M&R) for the eight alternatives are estimated by a professional cost estimation engineer who has a long experience in estimating in construction building. The salvage value in this study is ignored since the exterior wall becomes useless after its insulation. Table 9 shows the case study's cost data and the LCC results.

In order to validate this result, a reference index percentage is used to estimate the LCC. According to Roper and Payant (2014), the annual M&R budget should be 2 to 4 percent of the current replacement value of the facilities, excluding land. However, this estimation percentage cannot be applied to materials such as air conditioning systems requiring continuous maintenance and high M&R cost. Since the exterior walls have low M&R cost, M&R annual cost in Table 9 is compared to these percentages, and all of the M&R cost was in the same range of 2% and 4%.

The LCC value needs to be normalized in the final step, according to equation 4, by dividing each value by the maximum value. The fourth column in the Table of Figure 6 shows the normalized LCC for the eight alternatives.

3.2.3.2 Step 2: calculation of Vs for the exterior wall alternatives and selecting the preferred one using the BIM model. The final step of the framework is to calculate the Vs for all eight
Figure 5. Screenshot of the eight wall assemblies as modeled in Revit.
alternatives. All the selected wall assemblies are modeled in the Revit model for the case study, and all CWs and values were entered. They were entered promptly using Dynamo by importing them from the Excel sheet. Also, material LCC cost was entered in task 1. Figure 7 shows an example of criteria values inputs in the BIM model. The model calculates the QW and V by dividing all normalized QW by normalized LCC as mentioned in the framework, as shown in Figure 6. Also, the figure shows all the eight alternatives are ranked from the highest value alternatives to the lowest one, and it also shows all the other material criteria parameters.

The preferred choice is the material with the maximum QW and the least LCC. The second column in the Table of Figure 6 represents the V of all eight alternatives using equation 6, as explained before. The highest value is Assembly 1, containing three layers (Insulated concrete block, Plaster, and Exterior Paint 0.1 cm). Even though its quality is not the maximum among all

| Cost | Initial Cost | M&R Annual Cost | LCC Cost |
|------|--------------|-----------------|----------|
| Unit | S.R/m²       | S.R/m²          | S.R/m²   |
| Assembly 1 | 193.05       | 5.79            | 2598.74  |
| Assembly 2 | 268.65       | 8.06            | 3616.43  |
| Assembly 3 | 290.25       | 8.71            | 3907.20  |
| Assembly 4 | 595.35       | 17.86           | 8014.30  |
| Assembly 5 | 662.85       | 19.89           | 8922.95  |
| Assembly 6 | 521.10       | 15.63           | 7014.78  |
| Assembly 7 | 575.10       | 17.25           | 7741.70  |
| Assembly 8 | 776.25       | 23.29           | 10,449.48|

Alt TEXT: Case study external walls cost data to calculate the LCC cost of the eight alternatives. All the M&R Cost has same range of 2% and 4% from Initial Cost.
alternatives, it is the highest value because of its low cost. Comparing manual calculation with BIM results concludes that the automation of BIM integration is valid.

3.2.4. Case study analysis and discussion
According to the proposed framework, this case study is done to properly validate the framework and ensure that all results are logical. Many material alternatives are selected as per the most common materials in the local market. Thus, the options for wall assemblies vary from painted walls to cladding, stone finish, and precast walls. All materials specifications and dimensions are taken from the commonly available materials in the local market.

The case study can be generated by expanding the eight external wall assemblies to more standard ones. However, many new technologies such as 3D printer houses and precast walls,
drywall manufactured in a factory that can control its quality and follow standards. El-Sayegh et al. (2020) reviewed the challenges of 3D printing in the future, promising to stand in their quality. Suntharalingam et al. (2021) studied the energy performance of 3D-Printed concrete walls by measuring the thermal transmittance value (U-value) and then comparing it with a standard.

Lee, (2018a) highlights such difficulties. The author attempts to develop a cost-effective evaluation of composite building materials such as flooring and wall system. In order to test two types of flooring systems (including the construction slab concrete and insulation), the researchers used a Korean apartment. There were just three possibilities for comparison. Lee (2021) provided a methodology for indexing function, cost, and value scores using the vector normalization method in another study. This model is used to select three different finishing material systems for a case study of an office floor building. These two studies are limited to case studies and composite options and are not generated with all composite building types.

|  | Criteria Weights | Quality Values | Initial Cost Values | Life Cycle Cost Values | Overall Value Results |
|---|---|---|---|---|---|
| Expert 1 | 85 | 90 | 100 | 90 | 100 |
| Expert 2 | 70 | 100 | 100 | 100 | 90 |
| Expert 3 | 90 | 70 | 90 | 70 | 80 |
| Satisfaction Average | 82% | 87% | 97% | 87% | 90% |

Alt TEXT: Experts' Satisfaction percentage value from 100% weight for the proposed framework.

3.3. Phase 3: Model validation
In addition to validation in the framework and the case study, the previous case study is presented to three expert engineers to validate its final results. The experts have been in the construction industry for more than 25 years. They work as managers in construction companies classified under class 1 contractors in Saudi Arabia. They were asked to express their satisfaction on a 1–100% scale about quality, cost, criteria weights, and overall value results. Their response is summarized in Table 10. The expert comments demonstrate that the suggested framework produces credible results that may be used to evaluate materials.

4. Conclusions
This research proposes a framework to evaluate exterior walls materials that help the decision-maker select the most valued materials between many alternatives. In this framework, nine selection criteria are identified and validated by three specialist experts and verified by a questionnaire. These criteria are wind load resistance, thermal insulation, weight, sound transmission, fire resistance, water penetration resistance, aesthetic, durability, and maintainability. The weight of each criterion varies according to the project function. In addition, eight external wall assembly alternatives are shown in Table 5, are weighted based on three expert judgments according to ordinary building conditions. The study methodology used four integrated methods to achieve the study objectives during the weighting process. These methods are VE, AHP, Pairwise, and FAST methods. An explanation of the proposed framework steps is provided to accomplish the research objective. All calculation methods and equations are stated. Finally, the process is connected and automated with the BIM model. The required parameters and the workflow of the BIM calculation are defined.

Furthermore, a commercial building case study is reported to understand the evaluation process better. The selection of the case study’s exterior walls material is reached using the proposed framework. The eight chosen wall assembly alternatives in the framework are used and evaluated in this case study by estimating the LCC and V based on three experts and using the Saudi local
market prices. The external wall assembly alternatives are ranked according to the BIM model’s material data and specifications.

Finally, to confirm the framework of this study, the results are evaluated by expert engineers. They evaluate quality values, cost values, the criteria weights, and the overall value results. The satisfaction average is more than 80%. That shows that the proposed framework gives a reliable evaluation of the value of each material alternative. The expert engineers discuss the proposed framework’s advantages and realistic results.

As an extension of this study, there is a requirement to study more external wall criteria weight toward standardized composites materials. Standardizing external walls is an important step to be programmed in BIM and facilities the selection process. In addition, the impact of extreme building conditions (such as locating in high wind, noisy, extreme weather, restricted external visual theme, or having a critical structure design that requires low wall weight) needs to be studied further.

Acknowledgements
The author would like to thank the Deanship of Scientific Research (DSR), the King Saud University (KSU), for supporting this research.

Funding
The author would like to thank the Deanship of Scientific Research (DSR), King Saud University (KSU), for supporting and funding this research.

Author details
Ammar M. Saud1
E-mail: oms1511@hotmail.com
ORCID ID: http://orcid.org/0000-0003-0785-2911
Khalid S. Al-Gahtani1
E-mail: kgahtani@ksu.edu.sa
ORCID ID: http://orcid.org/0000-0002-9555-2443
Abdullah M. Alsugair1
E-mail: omsugair@ksu.edu.sa
ORCID ID: http://orcid.org/0000-0002-9849-7611
1 Civil Engineering Department, King Saud University, Riyadh, Saudi Arabia.

Disclosure statement
No potential conflict of interest was reported by the author(s).

Citation information
Cite this article as: Exterior wall selection framework using Building Information Modeling (BIM), Ammar M. Saud, Khalid S. Al-Gahtani & Abdullah M. Alsugair, Cogent Engineering (2022), 9: 2088642.

References
Al-Hammad, A. M., Hassainain, A. M., & Juaim, N. M. (2016). Evaluation and selection of curtain wall systems for medium-high rise building construction. Structural Survey, 32(4), 299–314. https://doi.org/10.1108/SS-10-2013-0035
Alshamrani, O. S., Abdul Mugeebu, M., Ashraf, N., Al-Ghonamy, A., & Alchouni, M. (2017). Selection of external wall material by LCC technique for office-cum-commercial building in the Eastern Province of Saudi Arabia. Journal of Architecture and Planning, 29 (2), 243–256. 10.1818-3604 https://cop.ksu.edu.sa/sites/cop.ksu.edu.sa/files/attach/jop_ksu_jul2017_e1.pdf
Azhar, S., Nadeem, A., Mok, J. Y., & Leung, B. H. (2008). “Building Information Modelling (BIM): A new paradigm for visual interactive modeling and simulation for construction projects”. In Proc., First International Conference on Construction in Developing Countries, Vol. 1, pp. 435–446.
Bogivo, C., Congedo, P. M., Fazio, A., & Laforgia, D. (2014). Multi-objective optimization analysis for high efficiency external walls of zero energy buildings (ZEB) in the Mediterranean climate. Energy and Buildings, 74, 483–492. 0378-7788. https://doi.org/10.1016/j.enbuild.2014.08.043
Bajno, D., Bednorz, L., Matkowski, Z., & Raszczuk, K. (2020). Monitoring of thermal and moisture processes in various types of external historical walls. Materials, 13(3), 505. https://doi.org/10.3390/ma13030505
Bapat, H., Sarker, D., & Gujar, R. (2021). Application of integrated fuzzy FCM-BIM-IoT for sustainable material selection and energy management of metro rail station box project in western India. Innovative Infrastructure Solutions, 6(2), 1–18. https://doi.org/10.1007/s41062-020-00431-7
Bhushan, N., & Rai, K. (2004). Strategic decision making applying the analytic hierarchy process. Springer BIMForum (2021). Level of Development (LOD) Specification, Part 1, Guide and Commentary. https://bimforum.org/lofd
Boostani, H., & Hančer, P. (2018, December). A model for external walls selection in hot and humid climates. Sustainability, MDPI, Open Access Journal, 11(1), 1–23. doi:10.3390/su11010100.
Boswell, K. (2013). Exterior building enclosures: Design process and composition for innovative façades. John Wiley & Sons
Carvalho, J. P., Villaschi, F. S., & Bragança, L. (2021). Assessing life cycle environmental and economic impacts of building construction solutions with BIM. Sustainability, 13(16), 8914. https://doi.org/10.3390/su13168914
Crane, F. A. A., Charles, J. A., & Furness, J. (1997). Selection and Use of Engineering materials (3rd ed.). Butterworth-Heinemann.
CSIF. (2011). The CSI construction contract administration practice guide. John Wiley & Sons.
Cunningham, T. (2013). Factors affecting the cost of building work—an overview. Dublin Institute of Technology.
D’Agostino, D., DeRossi, F., Mariglione, M., Marino, C., & Minichilli, F. (2019). Evaluation of the optimal thermal insulation thickness for an office building in different climates by means of the basic and modified “cost-optimal” methodology. Journal of Building Engineering, 24, 100743. https://doi.org/10.1016/j.jobe.2019.100743
Dell’Isola, A. (1997). Value engineering: Practical applications . . . for design, construction, maintenance and operations. Wiley.
Diamini, S. (2012). Relationship of construction sector to economic growth. In International congress on construction management (Canada: International Congress on Construction Management).

El-Sayegh, S., Romdhane, L., & Mangjikia, S. (2020). A critical review of 3D printing in construction: Benefits, challenges, and risks. Archives of Civil and Mechanical Engineering, 20(2), 1–25. https://doi.org/10.1007/s43452-020-00038-w

Eltarabishi, F., Omar, O. H., Alyouf, I., & Bettayeb, M. (2020). “Multi-criteria decision making methods and their applications—a literature review”, Proceedings of the International Conference on Industrial Engineering and Operations Management, Dubai, UAE (IEOM Society International), March 10–12, 2020

Fazeli, A., Jalaei, F., Khanzadi, M., & Banishahemi, S. (2019). BIM-integrated TOPSIS-fuzzy framework to optimize selection of sustainable building components. International Journal of Construction Management 1–20. https://doi.org/10.1080/15623559.2019.1686836

Grob, G. R. Importance of ISO and IEC international energy standards and a new total approach to energy statistics and forecasting. (2000). Applied Energy, 76(1–3), 39–54. 0306-2619. https://doi.org/10.1016/S0306-2619(03)00045-X

Hamdan, S., & Cheaitou, A. (2017). Supplier selection and order allocation with green criteria: An MCDM and multi-objective optimization approach. Computers & Operations Research, 81, 282–304. 0305-0548. https://doi.org/10.1016/j.cor.2016.11.005

Heaton, J., Parlikad, A. K., & Schooling, J. (2019). Design and development of BIM models to support operations and maintenance. Computers in Industry, 111, 172–186. 0166-3615. https://doi.org/10.1016/j.compind.2019.08.001

Heidari Matin, N., & Eydgahi, A. (2021). A data-driven optimized daylight pattern for responsive facades design. Intelligent Buildings International, 1–12. https://doi.org/10.1080/17508975.2021.1872478

Ho, W., Xu, X., & Dey, P. K. (2010). Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. European Journal of Operational Research, 202(1), 16–24. https://doi.org/10.1016/j.ejor.2009.05.009

Iribarren, D., Marvuglia, A., Hild, P., Guittou, M., Popovic, E., & Benetto, E. (2015). Life cycle assessment and data envelopment analysis approach for the selection of building components according to their environmental impact efficiency: A case study for external walls. Journal of Cleaner Production, 87, 707–716. 0959-6526. https://doi.org/10.1016/j.jclepro.2014.10.073

Jaccosi, C., & Hoffmeister, L. M. (2018). Potential use of BIM for automated updating of building materials values. Brazilian Journal of Operations & Production Management, 15(1), 35–43 https://doi.org/10.14468/BJJOPM.2018v15n1.04

Jollozidzechahri, E., Vadiee, A., & Johansson, P. (2019). Achieving a trade-off construction solution using BIM, an optimization algorithm, and a multi-criteria decision-making method. Buildings, 9(4), 81. http://www.mdpi.com/2075-5309/9/4/81

Khanzadi, M., Koveh, A., Moghadam, M. R., & Pourbagheri, S. M. (2019). Optimization of building components with sustainability aspects in BIM environment: Optimization of building components with sustainability aspects in BIM environment. Periodica Polytechnica Civil Engineering, 63(1), 93–103. https://doi.org/10.3311/PPCi.12551

Lee, J. (2018). Value engineering for defect prevention on building facade. Journal of Construction Engineering and Management, American Society of Civil Engineers (ASCE), 144(8) 04018069. 04018069-1. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001500.

Lee, J. (2021). Indexing model based on vector normalization available for value engineering in building materials. Applied Sciences, 11(20), 9515. https://doi.org/10.3390/app11209515

Lin, Z.-C., & Yang, C.-B. Evaluation of machine selection by the AHP method. (1998). Journal of Materials Processing Technology, 57(3–4), 253–258. 0924-0136. https://doi.org/10.1016/S0924-0136(95)02076-4

Liu, F.-H. F., & Hoi, H. L. (2005). The voting analytic hierarchy process method for selecting supplier. International Journal of Production Economics, 97 (3), 308–317 https://doi.org/10.1016/j.ijpe.2004.09.005. 0925-5273

Loganin, V. (2020). Influence of moisture on the durability of protective and decorative coatings of external walls of buildings. In MATEC Web of Conferences (Vol. 329). EDP Sciences.

Ma, W., Yin, Y., Yang, G., Li, Q., & Lu, B. (2019). Comprehensive performance evaluation method of green materials for coastal buildings based on BIM. Journal of Coastal Research, 93(sp1), 304–309. https://doi.org/10.2112/SI93-040.1

Marzouk, M., Abdelhamid, M., & Elsheikhi, M. (2013). Selecting sustainable building materials using system dynamics and ant colony optimization. Journal of Environmental Engineering and Landscape Management, 21(4), 237–247 doi.org/10.3846/16488897.2013.788506.

Mayhoub, M. M., Ibrahim, M. G., Sayod, Z. M., & Ali, A. A. (2019). “Development of green building materials’ evaluation criteria to achieve optimum building facade energy performance”, 2019 International Conference on Sustainable Energy Engineering and Application (ICSEEA), 1–8.

Nadoushani, Z. S. M., Akbarnezhad, A., Jornet, J. F., & Xiao, J. Multi-criteria selection of façade systems based on sustainability criteria. (2017). Building and Environment, 121(2017), 67–78. 0360-1323. https://doi.org/10.1016/j.buildenv.2017.05.016

Najjar, M. K., Figueiredo, K., Evangelista, A. C. J., Hammad, A. W. A., Tam, W. V. Y., & Haddad, A. (2019). Life cycle assessment methodology integrated with BIM as a decision-making tool at early-stages of building design. International Journal of Construction Management, 541–555. https://doi.org/10.1080/15623599.2019.1637098

Nirmal, N. P., & Bhatt, M. G. (2016). Selection of automated guided vehicle using single valued neutrosophic entropy based novel multi attribute decision making technique. Florentin Smarandache, Surapati Pramanik, 105 105–114

Owada, M., Anumba, C., & Asadi, S. (2018). Decision support system for building materials selection: Current trends and opportunities. In Construction research congress 2018: Sustainable design and construction and education. https://doi.org/10.1061/9780784481301.058

Ried, R. N. (2008). Roofing & cladding systems: A guide for facility managers. The Fairmont Press, Inc.

Roper, K., & Payant, R. (2014). The facility management handbook. Arcomac.

Saud Standards, Metrology and Quality Organization (SASO) (2022), https://saso.gov.sa/
Saud, (2022), “Saudi energy conservation code—residential”. Saudi building Code National Committee.

Shahinur, S., Ullah, A., Noor-E-Alam, M., Haniu, H., & Kubo, A. (2017). A decision model for making decisions under epistemic uncertainty and its application to select materials. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 31(3), 298–312. https://doi.org/10.1017/S0890060417000191.

Smith, D. J. (2017). Reliability, maintainability and risk: Practical methods for engineers. Butterworth-Heinemann.

Song, B., & Kang, S. (2016). A method of assigning weights using a ranking and nonhierachy comparison. Advances in Decision Sciences, 2016, 9 Article ID 8963214, Hindawi Publishing Corporation. https://doi.org/10.1155/2016/8963214

SOTA. (2019). “State of the art acoustik”. Retrieved 03, 2019, from http://www.sota.ca/aistc.html

Suntharalingam, T., Upasiri, I., Gatheeshgar, P., Poologanathan, K., Nagaratnam, B., Santos, P., & Rajanayagam, H. (2021). Energy performance of 3D-printed concrete walls: A numerical study. Buildings, 11(10), 432. https://doi.org/10.3390/buildings11100432

Taylor, H. (2014), “Cost of constructing a home”, HousingEconomics.com

Yazdani, M. (2018). New approach to select materials using MADM tools. International Journal of Business and Systems Research (IJBSR), 12(1), 25–42. https://doi.org/10.1504/IJBSR.2018.088454

Zardari, N., Ahmed, K., Shirazi, S., & Bin Yusop, Z. (2015). Weighting methods and their effects on multi-criteria decision making model outcomes in water resources management. Springer International Publishing. https://doi.org/10.1007/978-3-319-12586-2

Zhang, F., Ju, Y., Gonzalez, E. D. S., Wang, A., Dong, P., & Giannakis, M. (2021). A new framework to select energy-efficient retrofit schemes of external walls: A case study. Journal of Cleaner Production, 289, 125718. https://doi.org/10.1016/j.jclepro.2020.125718