Decision Support System for Material Selection based on Supplier Rating

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Abstract –

Buildings are continuously recognized as being responsible for significant amount of carbon emission to the environment. A good way to reduce this emission is through the choice of appropriate materials. However, selection of buildings materials is typically based on a number of factors, some of which can either be cost or environmental related. The selection process becomes complicated when designers are faced with several material options of building elements and each option can be supplied by different suppliers whose selection criteria may affect the budgetary and environmental requirements of the project. In order to help decision makers select the most appropriate materials, this paper proposes a decision support system which integrates a modified harmony search algorithm, building information models and supplier performance rating. To illustrate the decision support system, this paper presents a case study of a building in Michigan. The system is capable of producing the cost and environmental implications of different material combinations or building designs.

Keywords –

Harmony Search Optimization; Supplier Rating; Material Selection

1 Introduction

There are a number of benefits to designing buildings that are both cost and environmentally friendly. These includes reduction in carbon-dioxide emission to the environment [1,2], embodied energy in buildings [3,4] and improvement of indoor air quality [5]. When designing buildings, designers are usually faced with the challenge of selecting the most suitable material from different material options or alternatives. This decision becomes more complicated when each material option can be supplied by different suppliers. Furthermore, each supplier may have ratings with different contributions towards the budgetary and environmental requirements of the project in terms of criteria such as price, quality of material and service. Depending on the rating assigned to each criteria, the budgetary and environmental impacts of a project could be affected. For example, if the quality of a material is of more importance to a designer, the cost of the material, hence, the project cost will be higher and if the supplier is selected for his low cost, other criteria such as suppliers material quality, distance and environmental considerations, may be dissatisfying. The later may result in increase in the projects total carbon emission and transportation costs. Although, there has been a number of studies addressing material selection, there is still limited study on the influence of supplier selection criteria on the budget and environmental considerations of a project.

Hence, this paper presents a framework for improving decision making in sustainable construction through appropriate selection of building materials. The framework integrates building information models (BIM), a modified harmony search optimization algorithm and supplier rating. The proposed system adopts two Leadership in Energy and Environmental Design (LEED) requirements pertaining to material selection. To illustrate the functionality of the system, a case study of an office building project in Michigan is discussed.

2 Background

In recent years, material selection has been addressed using different approaches such as ranking methods and optimization techniques. Castro-Lacouture, *et al.* [6] proposed a mixed integer linear programming for material selection using LEED rating. Florez and Castro-Lacouture [7] also utilized mixed integer linear programming but considered objective and subjective factors. Chan and Tong [8] proposed a multi-objective optimization model that uses grey relational analysis to simulate all design criteria and requirements. Zhou, *et al.* [9] developed a multi-objective optimization model for sustainable material selection that includes factors such as process, cost, mechanical properties, performance and environmental impact. Rao [10] proposed an improved compromised ranking method for material selection considering material attributes and their relative importance. Jee and Kang [11] utilized a ranking method to rank materials according to their level of fulfilment of several requirements. Chatterjee, *et al.* [12] explored the capability of the complex proportional assessment and evaluation of mixed data methods for ranking alternative materials according to their capability of meeting predefined design requirements. In spite of these efforts, there has been limited or no study on the effect of the weights of supplier selection criteria on budget and environmental considerations during decision making involving material selections.

3 Proposed System

This section presents an architecture of the decision support system for material selection. The system architecture (shown in Figure 1) integrates BIM, Microsoft database and a modified harmony search algorithm.

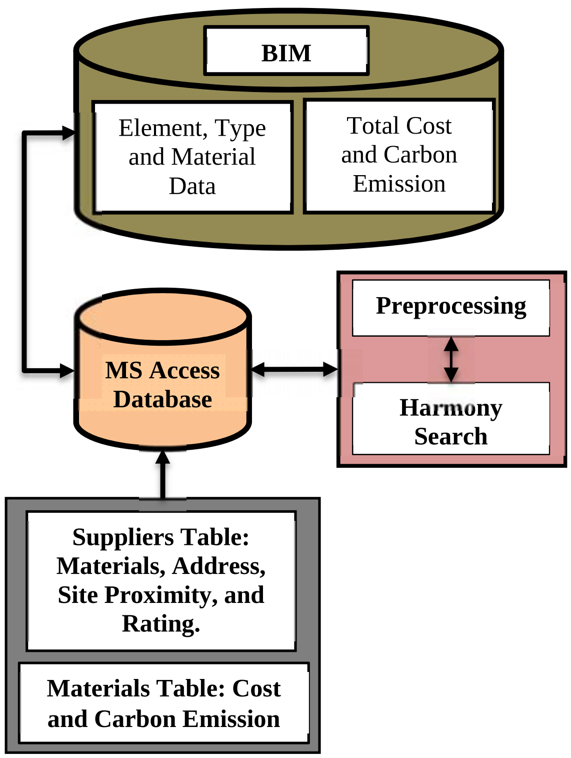

Figure 1. System Architecture for Material Selection

The overview of the information flow among the various applications in the proposed framework is shown in Figure 2. The stages of the model are described below:

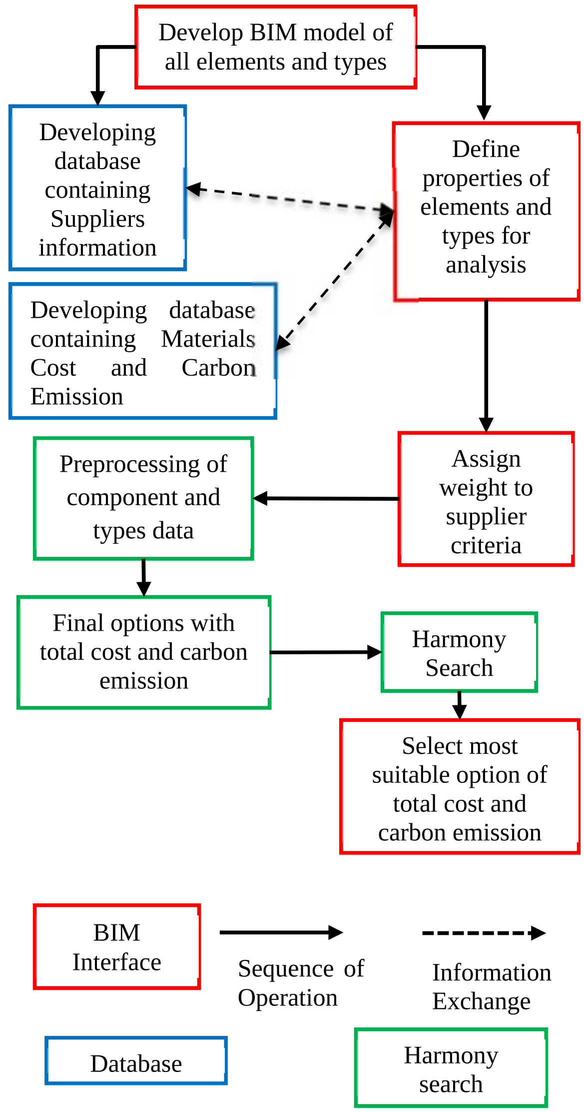

Figure 2. Information flow in Decision Support System.

3.1 Step 1: BIM Module: Defining Building Elements and Properties

In step 1, the building elements and types of each element are defined in the BIM model. The following element properties are also defined: alternatives of each material, the elements to be included in the simulation and elements to be considered for LEED analysis. Autodesk Revit architecture was utilized as the BIM tool. LEED points are also defined in the BIM model. Credit 5 (the regional materials) is implemented for each material option by checking the LEED property (within BIM) for the suppliers in 500 miles range around the project's location.

Table 1: LEED Credits Considered in this Research

Credit	Points	Intent	Requirement
Credit 4	1 point	To increase demand for building products that incorporate recycled content materials, thereby reducing impacts resulting from extraction and processing of virgin materials	Minimum percentage materials recycled for each point threshold = 10% of the total value based on cost
	2 points		Minimum percentage materials recycled for each point threshold = 20% of the total value based on cost
Credit 5	1 point	To increase demand for building materials and products that are extracted and manufactured within the region, thereby supporting the use of indigenous resources and reducing the environmental impacts resulting from transportation	Minimum percentage regional materials for each point threshold = 10% of the total value based on cost
	2 points		Minimum percentage regional materials for each point threshold = 20% of the total value based on cost

3.2 Step 2: BIM-Microsoft Access database

The list of materials, cost and carbon emissions and the supplier information are contained in two separate tables within a Microsoft access database (shown in Tables 1 and 2). The supplier information includes addresses, materials supplied, performance rating and proximity to the construction site. The second table contains a list of building materials, their cost and carbon emission. This can be obtained from published inventories such as the inventory of carbon and energy [18]. The contents of the database and the inputs (from step 1) will be the inputs to the harmony search optimization. A plugin was developed within BIM that enables extraction of supplier data from the supplier database for input to the harmony search optimization.

In order to determine the most suitable supplier of each material alternative, it is important to evaluate and rate the suppliers. To accomplish this, a set of criterions were established, to compare the suppliers. A review of 36 articles on supplier selection criteria (from 1996-2014) was conducted to determine the most influential supplier criterions. From the review, quality was identified as the most popular criterion, followed by cost, while distance and environmental considerations have the lowest percentages. These four criterion were considered in the analysis. Cost refers to the piece-part prices of the type/material of a component as determined by the supplier; distance refers to the distance between the supplier and the jobsite. This affects freight charges, in addition to contributing to the overall carbon emissions of a project. Quality relates to the quality control tool used, defect rates, quality certifications and quality control inspection methods of the supplier. Environmental considerations determines whether the materials offered by the supplier contains recycled or reused content, or whether the supplier has any other environmental certificates for his materials [27]. This is the second LEED credit utilized in the framework (Credit 4: Recycled content).

Likert scale was used as the rating system. Likert scale is based on a 1-5 scale, where 1 means 'not preferred', and 5 means 'mostly preferred' (Table 3). This rating system has previously being adopted by other authors [28,29]. For each supplier, each criterion is assigned a rate in the range of 1 and 5 based on the designer's degree of satisfaction. Furthermore, depending on the designer's needs, the final score of a supplier is determined by assigning each criterion a weight between 0 and 1.

The plugin extracts element properties from BIM, the material and supply information from the database for use in the harmony search optimization. The plugin also extracts the supplier information from the database and displays this on the Revit interface so that the designer can assign suppliers to each material. After assigning suppliers to each material, the plugin extracts these information for the next step.

Table 2: Guideline for Supplier Rates [13]

Point	Grade	Description
5	Exceptional	Demonstrates substantially excellent performance, and has been in the excellence category for last 12 months
4	Excellence	Exceeds company's and customer's expectations, demonstrates extra effort, and is superior to vast majority of suppliers
3	Good	Meets the company's expectations
2	Acceptable	Meets company's minimum requirements
1	Poor	Does not meet the company's and customer's minimum acceptable level

3.3 Step 3: Harmony Search Optimization

Harmony search algorithm is an optimization method for solving both discrete and continuous variable problems. HS algorithm is inspired by the behaviour of musicians whereby each player searches for a better state of harmony. Furthermore, the aesthetic quality is determined by the pitch of each musician's instrument just as the objective function is determined by the set of values assigned to each design variable. Also, the quality of the sound is improved by constant practice just as the value of the objective function is improved by an increase in the number of iterations. HS algorithm requires only few parameters and can be easily implemented. HS has been successfully applied to a variety of practical or real-world optimization on problems, thus, offering more advantages than traditional optimization techniques. These advantages includes utilizing less mathematical requirements, engaging in random or stochastic search and generating a new solution vector, after considering previous vectors. These advantages demonstrate the flexibility of the HS algorithm and potential for producing better solutions. The stages of the harmony search model are described below:

3.3.1 Preprocessing Stage

The pre-processing stage serves two purposes:

1. To arrange the options of each component in an acceptable way to the harmony search stage. This is accomplished by determining the enumerated combinations between each type/material of a component and suppliers. Figure 3 illustrates the pre-processing process of curtain walls. From the figure, the designer has the option of selecting from two types of curtain walls and each curtain wall can be supplied by three suppliers.
2. To compute the cost and carbon emissions for each generated option in a way that incorporates the suppliers' scores using Equations (3) and (4). The results of Equations (3) and (4) are utilized in the HS stage for optimization.

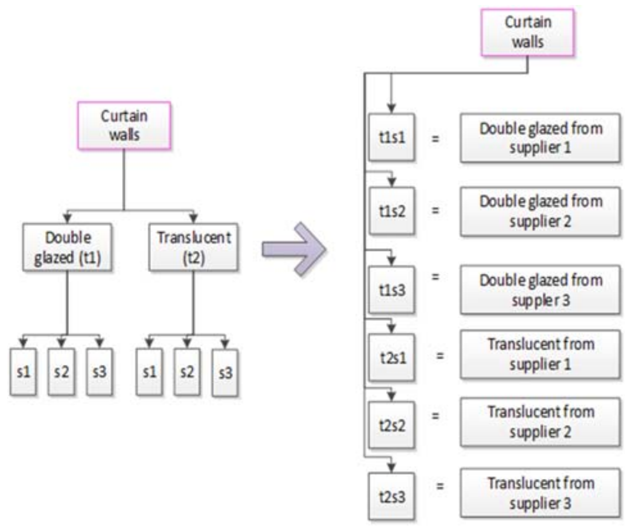

Figure 3. Pre-processing with an example of curtain walls

Computations of Total Cost and Carbon Emission: In computing the cost and carbon emission of buildings, the following phases need to be considered: preconstruction, construction, operations and end of life phases. Based on these phases, the total cost per unit of a material (TC) can be estimated as:

$$TC = C_1 + C_2 + C_3 + C_4 \qquad (1)$$

Where, C_1, C_2, C_3, and C_4 are the unit cost of a material in the preconstruction, construction, maintenance and demolition phases respectively.

Likewise the total carbon emissions per unit of a material (TCE) can be estimated as below:

$$TCE = C_1 + C_2 + C_3 + C_4 \qquad (2)$$

Where, E_1, E_2, E_3 and E_4 are the unit carbon emissions of a material in the preconstruction, construction, maintenance and demolition phases respectively.

Computations of Modified Total Cost and Carbon Emission: To account for the effect of the supplier rating and selection, Equations (1) and (2) are modified to Equations (3) and (4). These equations can be constructed as a weighted sum of the partial cost/carbon emissions, and are based on the following logics:

- Dividing the initial cost by the cost criterion rate: this means that when a supplier has a good price, the score will be high. This will decrease the initial cost, and in turn reduce the total value. Thus, making this material more probable to be chosen as an optimal solution;
- Dividing the transportation cost by the distance criterion rate: The transportation cost is directly related to the distance of supplier from the jobsite. In the same way, if the supplier is close, he will get a higher rate, which will decrease the transportation cost, and make the material more probable to be chosen as an optimal solution;
- Dividing the total cost by the quality criterion rate: The quality of a material affects the cost. If a material has a good quality, it will probably have a higher cost;
- Dividing the initial carbon emissions by the environmental considerations criterion rate: There is a difference in initial carbon emissions between the virgin and recycled/reused materials. As such, if the supplier provides products with recycled/reused materials, he will get a high score and that will reduce the initial carbon emissions. Hence, this material will probably be selected as an optimal solution.

$$Modified\ TC = \frac{\frac{C_i}{w_C * sc_c} + C_o + \frac{C_t * distance}{w_d * sc_d}}{w_q * sc_q} \quad (3)$$

$$Modified\ TCE = \frac{E_i}{w_e * sc_e} + E_o + \frac{E_t * distance}{w_d * sc_d} \quad (4)$$

Equations (3) and (4) represents components with only one material. Where, C_i is the initial cost of the material, $C_o = C_2 + C_3 + C_4$ and (C_t*distance) is the transportation cost. w_c, w_d, w_q and w_e are the weights assigned to the cost, distance, quality and environmental consideration criteria, respectively. sc_c, sc_d, sc_q and sc_e are the scores given to a supplier for the cost, distance, quality and environmental consideration criteria, respectively. E_i is the initial carbon emissions of a material, $E_o = E_2 + E_3 + E_4$ and (E_t*distance) is the carbon emission from transportation of a material.
In the case of components such as metal studs which consists of multiple materials, the Equations (3) and (4) becomes Equations (5) and (6):

$$Modified\ total\ unit\ cost = \sum_{j=1}^{m} \left(\frac{\frac{initial\ cost}{w_C * sc_c} + C_o + \frac{C_t * distance}{w_d * sc_d}}{w_q * sc_q} \right) j \quad (5)$$

$$Modified\ total\ unit\ carbon\ emissions = \sum_{j=1}^{m} \left(\frac{initial\ carbon\ emissions}{w_e * sc_e} + E_o + \frac{E_t * distance}{w_d * sc_d} \right) j \quad (6)$$

Where, m is the number of materials constituting a type of component

3.3.2 Harmony Search Stage

The objective function of the search process is to minimize the lifecycle cost and carbon emission of a building as shown in equations (7) and (8) respectively. This objective function is evaluated by simulating random values which are initially assigned to the design variables. Depending on the results of the simulation, the design variables are re-assigned new values and another simulation is performed to evaluate the objectives of the new design. The new values of the design variables can be chosen either by random or using the best obtained values which are already stored in harmony memory of the algorithm. In case the new solution is better than the worst solution available in the harmony memory, the worst solution is replaced by the new solution. As optimization process proceeds, the solutions stored in harmony memory becomes better and gradually approaches the optimum solution. The process is continued until a pre-specified maximum number of iterations is reached.

$$\min Cost = \sum_{i=1}^{n} C_i \quad (7)$$

$$\min Carbon\ Emissions = \sum_{i=1}^{n} CE_i \quad (8)$$

Where, n = number of variables, C_i and CE_i are the total cost and carbon emissions of the chosen alternative of a specific variable, respectively.

3.4 Step 4: BIM Module: Selecting the Most Suitable Option

The BIM module aims to present the designer with different designs options and the values of their cost and carbon emissions. Each design will have different combinations of materials. The designer can visualize the different options of total cost and carbon emissions. The selected option is typically the preferred design. However, in order to enable the designer understand the effect of different contributing weights on the supplier criteria, five scenarios were developed. Each scenario represents different weight criterions assigned to each of the supplier selection criteria. The details of the scenarios are shown in Table 3. In this stage, the designer can vary the weights assigned to each criterion depending on the objectives of the design. For example, from scenario 1, the designer can assign equal weights (i.e. 0.25) to each criterion or from scenario 2, he can assign 0.7 to cost and 0.1 to the other criteria. After the harmony search optimization, the designer can select from multiple options of total cost and carbon emissions.

Table 3. Weights assigned to each criterion

Scenarios	Weights
1	Equal weights of 0.25
2	Cost is assigned a higher weight of 0.7, other criterions were given a weight of 0.1
3	Quality was given a higher weight of 0.7, other criterions were given a weight of 0.1
4	Environmental Considerations was given a higher weight of 0.7, other criterions were given a weight of 0.1
5	Distance was given a higher weight of 0.7, other criterions were given a weight of 0.1

4 Case Study

An office building with a total floor area of 34,132 m^2 was used for the case study. The building consists of exterior masonry walls, double glazed curtain walls, precast plank with a concrete topping floor, double glazed curtain walls, exterior doors, hard board wood interior doors, fixed wood framed windows and metal stud-plaster board interior walls. The building was modelled using Autodesk Revit Architecture 2014. A Microsoft access database was developed. The database consist of two tables: One of the tables contains a list of building materials, their cost and carbon emission and the other table contains a list of suppliers, their addresses, materials they supply and their proximity to site. A plugin interface (in C#) was developed to enable interaction between the building components, the database and a harmony search optimization algorithm.

After developing the BIM model, the designer selects elements to be included in the analysis by checking the 'Analysis' property of the elements. The following elements were considered in this analysis: walls, doors, floors, windows, plumbing pipes and HVAC ducts. Table 4 shows the list of elements, types and materials. As part of the properties, alternative materials are assigned to each element (from Table 4) in the BIM model. If the project is to be considered for LEED certification, the 'LEED' property of each element is also checked. The developed plugin is then loaded from the 'add-in' menu of the BIM model. On loading the plugin, the designer selects any model element under the project elements and a list of associated materials (from the properties) are populated in a 'listbox' on the model interface as shown in Figure 5. On selecting any of the materials, the corresponding suppliers (from the database) are also populated on the model interface. The designer can select the potential suppliers of the materials. As each element, material and suppliers are selected from the model, the plugin will upload these information in a new table (in the database) alongside the cost and carbon emission data of the materials.

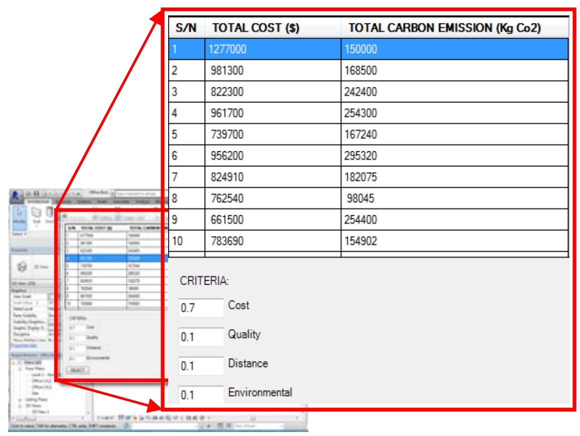

Figure 5. Model Interface showing results.

On selecting the suppliers, it is important to rate them according to their performance in respect to a set of criteria defined in section 2. The scores were assigned randomly, since these information cannot be obtained from the supplier's website. Suppliers whose products consider LEED were assigned the highest score of 5 for environmental considerations while suppliers whose products have any other environmental certificates were assigned a lower score of 4. However, suppliers whose products have no environmental certificate were assigned the lowest score of 1. Suppliers whose location was closer to the project site were assigned a high distance score of 5 and vice versa.

After rating the suppliers, depending on the objective of the design, the designer assigns different weights to each criterion (shown in Table 3). The analysis commences by executing the pre-processing stage. In this stage, the cost and carbon emission of each material are computed using Equations (5) and (6) from section 2.

The HS optimization uses the materials cost and emission data to search for the optimal solutions. The objective functions are shown in equations (1) and (2). The variables are the elements (labelled from X1-X6) in Table 4. The pitch adjustment (PAR) and harmony memory consideration rates (HMCR) helps the algorithm search for a better solution than the worst individual in the harmony memory [14]. The maximum and minimum PAR were set as 0.9 and 0.4 respectively, while the HMCR was 0.8. For each of the scenarios, the plugin can display the total cost and carbon emission of the project on the interface of the model.

Table 4. List of Components, Types and Materials

Components	Types	Materials
X1 = Exterior walls	Wood stud 1	Wood stud + plywood sheathing + steel veneer
	Masonry 2	Brick blocks + plywood sheathing+ steel veneer
	Metal stud 1	Metal stud + plywood + brick veneer
X2 = Curtain walls	Single glazed	
	Double glazed	
	Storefront	
	Translucent	
X3 = Exterior doors	Embossed panel steel	
	embossed half glass steel	
	French	
X4 = Plumbing pipes	0.5 in. brass	
	0.5 in. plastic	
	0.5 in. stainless steel	
X5 = HVAC ducts	Aluminum alloy under 100 lb	
	Galvanized steel under 200 lb	
	Fibrous-glass 1” thick	

5 Results

This section presents the results of the harmony search optimization. Tables 5 and 6 shows the optimal solutions for the case-study described in Section 3, considering scenarios 1 and 2. Three points have been selected from the optimal solutions of each scenario. Point 1 represents the solution with the highest cost but lowest carbon emission, point 3 represents the solution with lowest cost but highest carbon emission and point 3 is a randomly selected intermediate point. Point 1 can be regarded as the optimal solution for situations where suppliers are selected solely based on cost. The same applies to point 3, which is obtained only when minimizations of carbon emissions is carried out.

Table 5. Optimal Solutions based on Scenario 1.

Variable	Type (Point 1)	Type (Point 2)	Type (Point 3)
X1	Metal Stud 1	Metal Stud 1	Metal Stud 2
X2	Store Front	Store Front	Store Front
X3	Wood Framed 2	Wood Framed 2	Wood Framed 2
X4	Embossed Half Glass Steel	Embossed Panel Steel	Embossed Panel Steel
X5	Wood Bi-Fold	Wood Bi-Fold	Wood Hard Board
Total Cost ($)	301,340.9	278,490.1	226,134.9
Total Carbon Emission (kg)	46,201.45	56,226.6	43,172.2

Table 6. Optimal Solutions based on Scenario 3.

Variable	Type (Point 1)	Type (Point 2)	Type (Point 3)
X1	Metal Stud 2	Metal Stud 2	Metal Stud 2
X2	Store Front	Store Front	Store Front
X3	Wood Framed 2	Wood Framed 4	Wood Framed 2
X4	Embossed Half Glass Steel	Embossed Panel Steel	Embossed Panel Steel
X5	Wood Bi-Fold	Wood Bi-Fold	Wood Hard Board
Total Cost ($)	301,720.3	480,650.0	392,280.5
Total Carbon Emission (kg)	78,585.4	68,520.8	51,593.2

6 Conclusions

This paper presents a framework for selecting building designs that are both cost and environmental effective by integrating BIM, a modified harmony search optimization algorithm and supplier rating. A modified harmony search optimization algorithm that includes supplier selection criteria and rating has been presented.

The search algorithm provides the values of the cost and carbon emissions of material alternatives. The case study illustrates the capabilities of the developed decision support system. The system shows good capability of practical material selection and building design. From a designer's perspective, time and effort could be saved through a BIM-based material selection tool that provides the cost and environmental implications of different design options.

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