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The Development of a Decision Support Model for Eco-Friendly Material Selection in Vietnam

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Abstract: In recent years, the awareness of sustainable construction has increasingly risen in countries around the world, with the main goal being to avoid depleting energy resources and raw materials and to greatly reduce carbon emissions. Therefore, the selection of eco-friendly building materials becomes a difficult task and choosing the best construction strategy is a complicated process. Most of the studies of the building material selection often focus on optimizing material-related green building scores with budget constraints based on the environmental impacts of those materials. However, these studies do not pay attention to the impact of sustainable materials on two important aspects of a project: The initial investment cost and the total labor-working days. Hence, this study developed a model that optimizes a material mix for buildings considering the building budget, total labor-working days, and material-related green building scores. A case study in Vietnam was conducted to illustrate the effectiveness of the proposed model. This proposed model provides a guidance for decision-makers in selecting approximate materials for buildings toward sustainability.

Keywords: green building; sustainable material; material selection; green building assessment system

1. Introduction

The construction sector plays a vital role in contributing to economic growth, satisfying the needs of society, enhancing the quality of life, and providing job opportunities. However, these constructions have caused an adverse effect on the environment such as generating half of the greenhouse gas emissions, using nearly 40% of the natural resources worldwide, consuming 70% of the electrical power and 12% of potable water, and producing 45–65% of the waste placed in landfills [1–3]. The effect of construction on the environment becomes particularly important in developing countries, which use a large number of resources for their construction activities. Buildings, as one of the construction activities, consume a large number of natural resources, especially in the non-operational phases, such as the production of materials and the procedure for dismantling and waste disposal [4]. Especially, developing countries are increasingly speeding up the pace of urbanization in terms of the construction of infrastructure works, especially high-rise buildings [5]. Therefore, it can be said that the construction industry has a strong influence on the natural environment.

Green buildings or sustainable constructions are interpreted as using fewer natural resources and increasing the use of materials and products that have a high level of recycling or reuse [6,7]. At the same time, this practice prevents environmental degradation throughout the building's life cycle due to the manufacturing and construction processes [8]. In order to assess the sustainability of a building, it is important to identify many different factors and to examine them in a specific and transparent way. In addition, these factors are often uncertain issues, requiring an approach to provide technical support for decision making in order to achieve the sustainability of a building [1,9–11]. Recent studies have identified the sustainable impacts during the lifecycle of building materials according to the life cycle assessment (LCA) method [12–14]; specifically, concerns regarding the sustainability of building materials increasing, which is considered a key indicator in all assessment tools to evaluate the overall sustainability of the building [15,16].

Furthermore, materials have been considered an essential element for building construction, and the building materials selection has a significant role in sustainable building design and is performed both in the early design stage and the working plan [11]. Accordingly, building materials are responsible for 10–20% of the total building energy consumption [17]. In Vietnam, the construction material manufacturing industry is one of the largest sectors consuming raw materials, energy, and generating emission. Moreover, in recent years, awareness of sustainable construction has been increasing in nations around the world with the main goal of avoiding exhaustion of energy resources, water, and raw materials [18].

Therefore, in order to minimize the impact of buildings in their lifecycle, green buildings (GBs) have emerged as a new philosophy, encouraging the use of eco-friendly materials and the practice of construction techniques to save resources and reduce construction waste [19]. The sustainable material problems have been treated extensively through ranking methods or quantitative methods [20–23]. According to Zolfani et al. [24], the process of selecting materials is often considered under various factors, such as the weight of the materials, the manufacturing process, the function, the product quality, the aesthetics, and customer satisfaction.

In order to minimize the environmental impact of construction, many countries are encouraging green building construction by using green building material. Therefore, numerous green building certification systems for sustainable construction have been established by green building councils. The effective use of building materials is evaluated by various rating systems to ensure the achievement of sustainability in buildings including Leadership in Energy and Environmental Design (LEED) of the US, the British Building Research Establishment Environmental Assessment Method (BREEAM), Green Standard for Energy and Environmental Design (G-SEEK)—Korea, Comprehensive Assessment System for Building Environmental Efficiency (CASBEE)—Japan, Green Mark in Singapore, Green Star in Australia, etc. [25].

The Vietnam Green Building Council (VGBC) in Vietnam was established in 2007 with an aim to raise awareness and build capacity for the development of green buildings in Vietnam, and the Lotus-based certification system was published [26]. The Lotus green building certification system is currently the focus of attention for investors and other stakeholders. Indeed, Lotus has built up a strong reputation in green building rating systems in Vietnam [27]. These certification systems are used as a strategy to not only assess and rate a building's environmental performance, but also to encourage and help designers and investors improve the performance of their buildings [28]. Table 1 summarizes a number of green building rating systems in various countries, including developed and developing countries.

Table 1. Some rating systems for green buildings across the world.

Countries	Green Building Rating Systems	Sources
US	Leadership in Energy & Environmental Design (LEED)	[29–31]
UK	Building Research Establishment Environmental Assessment Method (BREEAM)	[32,33]
Australia	Green Star	[34,35]
Singapore	Green Mark	[36]
Vietnam	Lotus	[26,37]

Numerous studies on the optimization of building materials take into account environmental objectives. Zang et al. [38] presented an optimal method under the cap-and-trade (C&T) mechanism for transporting and storing construction materials to reduce carbon emissions during the project implementation towards sustainable development. A case study for the design of the new low-cost residential building was used to provide a Pareto front of the multi-criteria problem [39]. This study used the mode FRONTIER optimization tool rel.4.3.0 by developed in MATLAB through the combination of various commercial materials based on the ITACA score. Moreover, the material selection problems were investigated by different optimization techniques [39–41].

Park et al. [42] proposed a credit optimization algorithm to minimize LEED costs. The calculation process could be applied to both ongoing and planned LEED projects. According to Castro-Lacouture et al. [40], the optimization model based on a modified LEED system for building evaluation in Columbia could obtain a detailed purchase plan about the materials that should be used and their extent of use under constraints on design and budget. The main purpose of these sustainability rating systems is to avoid the depletion of natural resources, water, and raw materials, and to contribute to preventing the degradation of the habitat on earth.

In Vietnam, one of the most frequently discussed issues to ensure sustainable development is the restriction on the use of traditional building materials affecting natural resources and the environment. Materials mainly use burning materials, so the production of these materials greatly affects the country's resources as well as the production process that also produces CO_2 into the environment. For this purpose, the Ministry of Construction of Vietnam delivered Decision 419/QD-BXD on "Plan of actions of the construction industry to implement the Green Growth Strategy" in 2017 and Decision 280/QD-TTg, issued by the Prime Minister on 13/03/2019, on "National Program on Energy Efficiency 2019–2030 period" [27]. Therefore, sustainable building materials have emerged in the marketplace as a choice for practitioners in the construction industry. A building is a complex system consisting of many different types of construction materials. Therefore, the effect of material selection on the lifecycle energy balance of a building is clearly a complex problem. Moreover, ensuring the construction project addresses environmental goals under budget constraints is a major challenge for designers and investors.

Selecting suitable materials for buildings can help decision-makers in achieving the desired environmental, economic, financial, and social benefits. However, selecting the most appropriate eco-friendly material for a particular building application, considering Lotus scores, is not an easy task and is a great challenge for the designers and building owners. According to the above studies, the literature has produced few works that deal with this optimization problem. Therefore, in order to help the building investors or designers in selecting appropriate materials in green buildings, this study developed a multi-objective optimization model to select eco-friendly building materials considering the budget, the total labor-working days, and materials-related green building scores. The building budget was determined intensively by the building owner while material-related green building scores were calculated based on the green building rating system (i.e., Lotus-based green building rating system in Vietnam). A commercial building in Danang City, Vietnam was selected as a case study to demonstrate the effectiveness of the proposed model.

The problem of selecting the most appropriate eco-friendly material for a particular building application, considering Lotus scores, is not an easy task and is a great challenge for the designers and clients. They need to consider a range of selection criteria as well as environmental requirements including proportion of material, energy consumption, low carbon emission features, reduction of cost, and total labor-working day. As a contribution of the study, the proposed model provides decision makers such as investors and designers with a guidance of eco-friendly material selection toward green buildings.

2. Problem Definition

2.1. Definition of the Optimization Problem

The problem in this study aims to build an eco-friendly material selection integrated platform that will enable building owners and designers to optimize decision making through knowledge of materials type, construction strategy, and the Lotus-based green building certification system in Vietnam (Figure 1).

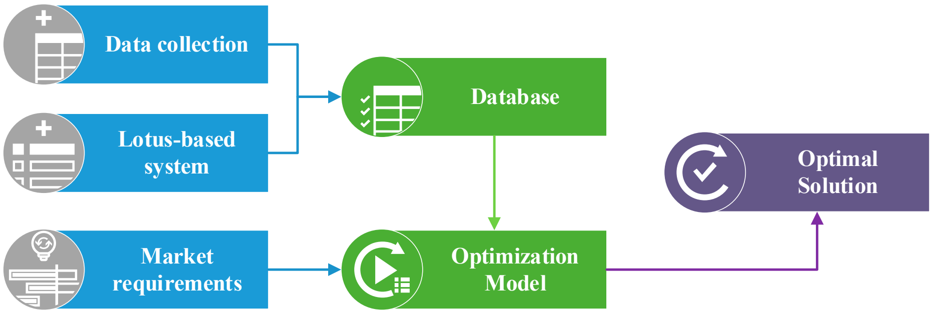

Figure 1. Optimization framework.

A given set of $X = [x_{i,j}]$ includes the decisive variables that represent the proportion of material i_{th} in category j_{th} to maximize the material score in the green building assessment systems (i.e., Lotus-based green building assessment system in Vietnam [27]). Let S be the set of building system (i.e., wood, brick, steel, cement, flooring, glass). Based on the above-mentioned problem, the proposed model should meet three main objectives, as shown below.

Maximize the rating score of eco-friendly materials (RS) in the building.

$$Max \sum_{i=0}^{n} (z_i * P_i) \tag{1}$$

Constraint to:

$$a\% * (\sum_{j=0}^{n} \sum_{i=0}^{m} (c_i * x_{ij} * d_i) \leq \sum_{j=0}^{n} \sum_{i=0}^{m} (r_i * x_{ij} * d_j * c_i) \tag{2}$$

$$l_{nj} \leq x_{\mathrm{ij}} \leq u_{nj}, j \in S, n = 1, 2, \ldots N(j) \tag{3}$$

$$\sum_{i=1}^{n} x_{ij} = 100\% \tag{4}$$

Minimize the initial investment cost (IC) for the building.

$$Min \sum_{j=0}^{n} \sum_{i=0}^{m} (x_{ij} * d_i * c_i) \tag{5}$$

Constraint to: Equations (3) and (4), and

$$\sum_{j=0}^{n} \sum_{i=0}^{m} (x_{ij} * d_j * c_i) \leq LB \tag{6}$$

Minimize the total labor-working days (LWD) that need to complete the building.

$$Min \sum_{j=0}^{n} \sum_{i=0}^{m} (x_{ij} * d_i * t_i) \tag{7}$$

Constraint to: Equations (3) and (4), and

$$\sum_{j=0}^{n}\sum_{i=0}^{m}(x_{ij} * d_j * t_i) \leq LP \tag{8}$$

where

LB: Limited material cost ($)
LP: Total limited labor-working days
c_i: Unit price of i_{th} material t_i
t_i: Standard hours to finish i_{th} material
d_j: Weight of j_{th} category of material
x_{ij}: Rate of i_{th} material in j_{th} category
z_j: The Lotus scores obtained in j_{th} category of the material.
$N(j)$: the maximum number of categories in the system j.
$a\%$: The percentage corresponding to each criterion of the sustainable materials in the Lotus-based system.
l_{nj}: The minimum rate of j_{th} material based on the requirement of the design.
u_{nj}: The maximum rate of j_{th} material based on the requirement of the design.

(Minimum and Maximum rate of j_{th} material are determined based on green building standards in Vietnam or requirements of building owners).

r_i: The type of sustainable material. According to the Lotus-based system [27], sustainable materials are divided into three categories such as (1) fast-growing renewable materials (grown and harvested within 10 years); (2) reusable materials or materials with at least 10% pre-consumer recycled components; or (3) 5% post-consumer recycled components, or materials with Volatile Organic Compounds (VOC) content <30 mg/L; where r_i = 1 is a sustainable material and r_i = 0 is an unsustainable material.

The problem in this study is to select the proportions of materials in buildings that can achieve the maximum of material-related green building scores within the budget constraint and the total labor-working days. The general objective function simultaneously accounts for the minimum value of material cost and total labor-working days to reach the desired Lotus scores as below

$$Min.f_{i,t} = \frac{RS_i}{IC_i * LWD_i} \tag{9}$$

In summary, the resulting model is comprised of the general objective function (9) subject to constraints (2)–(4), (6), and (8). To reveal, the existing trade-off is between building material cost, total labor-working days, and Lotus scores.

2.2. Generalized Reduced Gradient-Based Nonlinear Optimization Model

The Generalized Reduced Gradient (GRG) method proposed by Lasdon et al. (1974) [43] is one of the most popular methods to solve problems of nonlinear optimization. The GRG is an extension of the reduced gradient method to accommodate nonlinear inequality constraints. The main idea of this method is to solve the nonlinear problem dealing with active inequalities. The variables are separated into a set of basic (dependent) variables and non-basic (independent) variables. Then, the reduced gradient is computed in order to find the minimum in the search direction. This process is repeated until the convergence is obtained [44].

The nonlinear program to be solved is assumed to have the form (10)

$$Minimize.f(x) \tag{10}$$

Constraint to

$$g_i(X) = 0, i = 1, \ldots, m \tag{11}$$

$$l_i \leq X_i \leq u_i, i = 1, \ldots, n \tag{12}$$

where X is n-vector and u_i, l_i are given lower and upper bounds $u_i > l_i$. The fundamental idea of GRG is to use the Equation (11) to express m of the variables called basic variables, in terms of the remaining n-m non-basic variables. This is also the way the Simplex method of linear programming operates.

This study use the Generalized Reduced Gradient (GRG) method in the standard Microsoft Excel Solver [45]. This tool has been proven in use over many years as one of the most robust and reliable approaches to solving difficult NLP problems. Figure 2 presents the flowchart of the proposed model that is based on the GRG nonlinear optimization algorithm [43]. The GRG method is a generalization of the reduced gradient method that can deal with nonlinear constraints and arbitrary bounds on the variables.

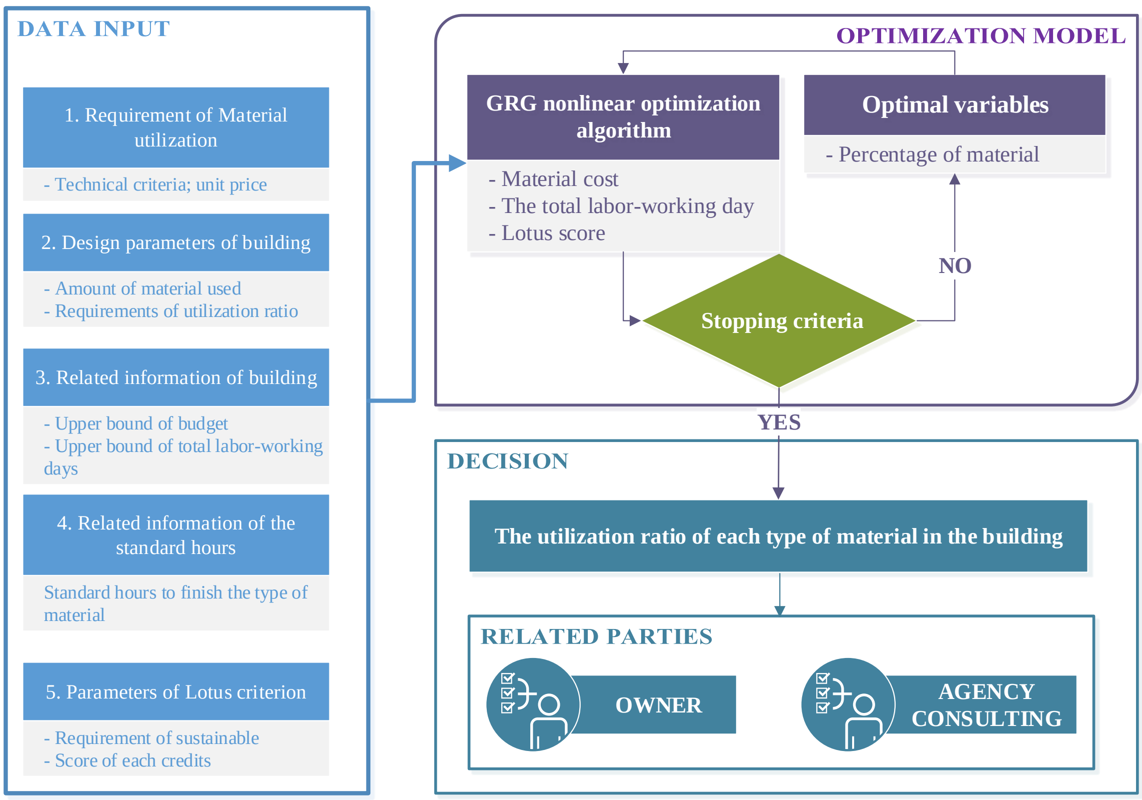

Figure 2. Optimization scheme for material selections.

The proposed model was implemented in the add-in function in Microsoft Excel [45] that is shown in Figure 2. The input data can be classified into five specific groups. The first group is the requirements for sustainable materials that include technical standards of materials, and unit prices of materials. The second group is the design parameters of the building that consist of the number of eco-friendly materials and the requirements of minimum and maximum material usage. The third group is the parameters related to the investor that are the estimated budget and expected construction time. The fourth group is the parameters related to the labor working days that requires for each type of materials. The last group is the score parameter related to the Lotus green building assessment system. Figure 3 shows experimental setting of the optimization model.

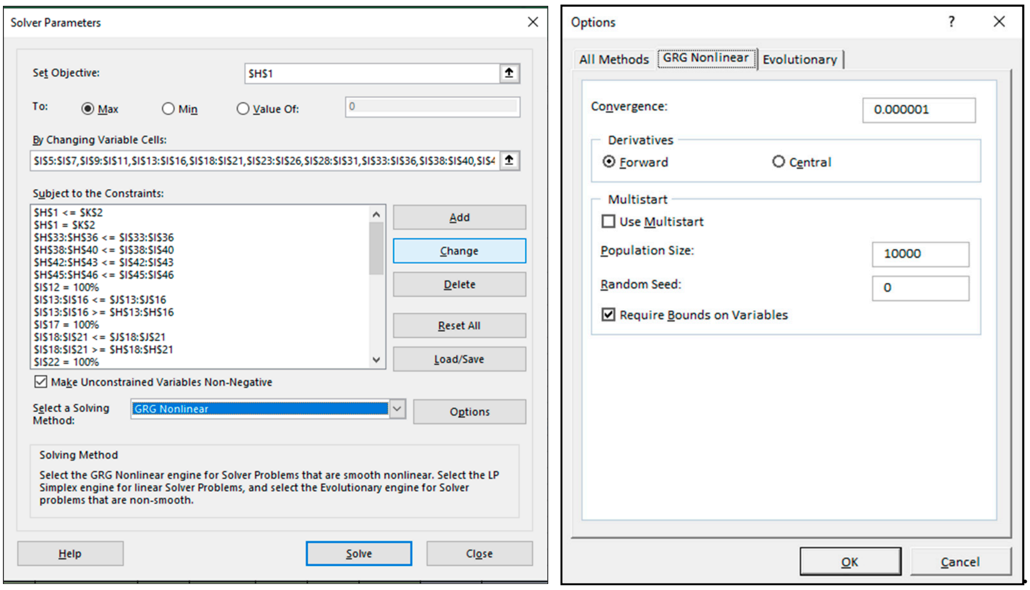

Figure 3. A snapshot of implementation of the proposed model.

3. Case Study

3.1. Lotus-Based Green Building Rating System

In Vietnam specifically, the Vietnam Green Building Council (VGBC) has developed the Lotus-based certification system with the ability to be applied to all types of construction projects [27]. The Lotus-based system is used to assess buildings regarding sustainability scores, indoor environment quality, and materials and resource usage. Green buildings are concerned by building stakeholders. In line with this development trend, the demand for construction materials will increase by about 10% per year, according to the Vietnam Association of Building Materials. By offering a common goal of saving construction materials, Lotus's material portfolio encourages solutions are beneficial to buildings because they maximize the reuse and recycling materials. Figure 4 shows the Lotus certified projects increase over the years. The Lotus-based system has built up a strong reputation in green building certification systems in Vietnam. The Lotus SB (Small Buildings) assesses new constructions and major refurbishments of non-residential buildings with a GFA of less than 2500 sqm. Figure 5 presents GUI of Lotus SB V1 in the certification system.

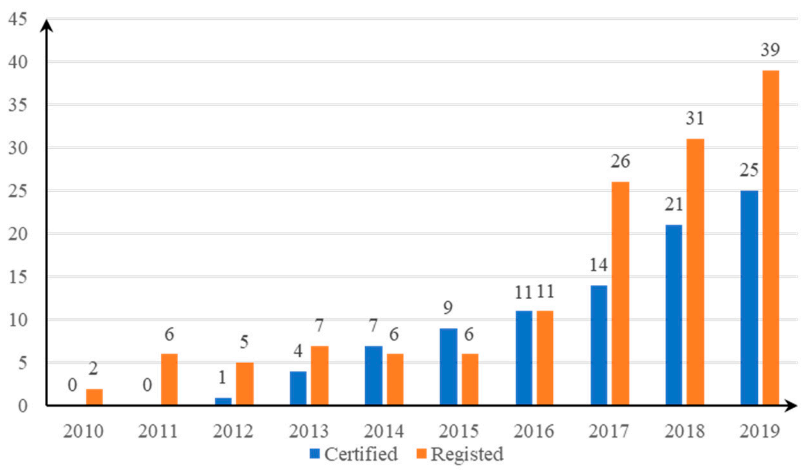

Figure 4. The total Lotus projects from 2010 to 2019 in Vietnam [27].

Figure 5. The screen of scorecard in the Lotus-based certification system [27].

According to the Lotus certification system, selections of eco-friendly materials encourages the use of local materials. The Lotus system also encourages the use of materials with a high level of recycling, a fast regeneration cycle, and low emissions to reduce their impact on the environment and on the indoor air quality of the building. Lotus's material portfolio includes three main goals: Minimizing the use of materials produced from new sources of extraction; encouraging the use of sustainable and low energy materials throughout the life cycle; and reducing construction waste. During the evaluation process, the Lotus system gives a high score for items that use fast renewable materials (planted and harvested within 10 years), reused materials, or materials with at least 10% pre-consumer recycled or 5% post-consumer recycled components. This system also recommends the use of materials with low VOC content to ensure the health of the occupants of the building.

3.2. Model Settings

The Danang International Airport Customs Headquarters was used as a case study to assess the applicability of the proposed model. Figure 6 presents the 3-D view of the experimental building that consists of five stories and a total floor area of 2450 m^2. The main building structures are reinforced concrete frame, brick walls, and reinforced concrete roofs.

Figure 6. Perspective of model launch facility.

Considering the above-mentioned facts, the selected actual building case study, named International Airport Customs Headquarters in Danang city, Vietnam (Table 2). The total estimated budget for the materials was $6,000,000, the total labor-working days was expected to result in 9000 days, and nine materials were considered including: Cement, steel, bricks, ceramic brick, glass, wood, floors, tiles, and paint. Table 3 presents the information on the materials used in the construction, including the material types, the quantity of the materials (d_j), the unit price of the materials (c_i), the standard days (t_i), and the sustainable material types (r_i). This information was derived from the construction company organization.

Table 2. Building's features and material information.

Building Information		Materials	Quanlity	Unit
Type of building	Office building	Steel	285	Ton
Status	New construction	Cement	800	Ton
Number of floors	5 + 1	Brick	210	m^3
Number of units	1	Wood	50	m^2
Land area	950 m^2	Glass	400	m^2
Gross area (total construction)	2450 m^2	Wood Flooring	1715	m^2
Height	22.2 m	Ceramic Tile Flooring	490	m^2
Total labor-working days	9000 days	Roof tile	125	m^2
Total estimated budget for material	$6,000,000	Paint	125	Lit

Table 3. Information on materials used in the construction.

ID	Materials	Symbol	d_j	c_i ($)	t_i (day)	r_i
1	Steel 1	St_1	285 (T)	13,380	3.2	1
	Steel 2	St_2		13,200	3.4	1
	Steel 3	St_3		14,500	2.8	0
2	Cement 1	Cm_1	800 (T)	1065	1.1	0
	Cement 2	Cm_2		1200	1.3	0
	Cement 3	Cm_3		1460	1.5	1
3	Brick 1	Br_1	210 (m^3)	600	2.4	0
	Brick 2	Br_2		1000	3.1	1
	Brick 3	Br_3		800	3.5	1
	Brick 4	Br_4		1200	3.2	1
4	Wood 1	W_1	50 (m^3)	880	1.4	1
	Wood 2	W_2		1650	1.6	1
	Wood 3	W_3		3000	1.25	0
	Wood 4	W_4		4500	1.3	0
5	Glass 1	Gl_1	400 (m^2)	620	0.7	0
	Glass 2	Gl_2		1000	0.85	1
	Glass 3	Gl_3		800	1	1
	Glass 4	Gl_4		630	0.6	0
6	Flooring 1	Fl_1	1715 (m^2)	170	2.3	1
	Flooring 2	Fl_2		180	2.5	1
	Flooring 3	Fl_3		230	1.8	0
7	Ceramic Brick 1	GS_1	490 (m^2)	191	1.9	0
	Green Brick 2	GS_2		220	2.3	1
8	Tile 1	T_1	125 (m^2)	15	1.4	0
	Tile 2	T_2		142	1.7	1
9	Paint 1	P_1	125 (lit)	212	1.5	1
	Paint 2	P_2		221	1.4	1
	Paint 3	P_3		160	1.9	0
	Paint 4	P_4		151	1.7	0

This building can reach a score of 13 in the green building rating system as its materials satisfy the requirements of the Lotus system. Table 4 shows information related to green building assessment in the Lotus system. The first category (M1) related to the structure materials. The building is evaluated with scores of 1, 2, and 3 if percentages of the sustainable structure materials are 40%, 60%, and 80% of the total material cost of the buildings, respectively. The second category (M2) refers to non-structural walls. The building achieves scores of 1, 2, and 3 as sustainable materials of the non-structural walls are 40%, 60%, and 80% out of the total material cost of the building, respectively. For the third category (M3) of window and door materials, if 40% of the windows and doors are made up of sustainable materials, 1 point is awarded, and if 80%, then 2 points are awarded. For the category of flooring (M4) and roofing materials (M5), the rating point system is as per the window and door materials. The last category corresponds to paint and overlay. If 50% of the material has a low volatile organic compound (VOC) level, the system gives 1 score.

Table 4. Lotus Small Building standards of materials.

Catalogy	Position	Building Components	Intention	Note	Symbol	Description	Score
M1	Material	Building structure	Rate of structure materials that is sustainable	* Rapidly renewable materials (grown and harvested within 10 years) * Reusable materials * Materials with at least 10% recycled pre-consumer components or 5% post-consumer recycled components * Autoclave materials	M1.1 M1.2 M1.3	40% of the structure materials are sustainable 60% of the structure materials are sustainable 80% of the structure materials are sustainable	1 2 3
M2	Material	Non-structural walls	Rate of non-structural walls that is sustainable	* Rapidly renewable materials (grown and harvested within 10 years) * Reusable materials * Materials with at least 10% recycled pre-consumer components or 5% post-consumer recycled components * Autoclave materials	M2.1 M2.2 M2.3	40% of the non-structural walls are sustainable 60% of the non-structural walls are sustainable 80% of the non-structural walls are sustainable	1 2 3
M3	Material	Windows and doors	The ratio of windows and doors made up of sustainable materials	* Rapidly renewable materials (grown and harvested within 10 years) * Reusable materials * Materials with at least 10% recycled pre-consumer components or 5% post-consumer recycled components * Autoclave materials	M3.1 M3.2	40% of windows and doors are made up of sustainable materials 80% of windows and doors are made up of sustainable materials	1 2
M4	Material	Flooring	Rate of flooring materials that is sustainable	* Flooring materials: Carpets, wood, plastic floors, hard floors * Exterior Concrete	M4.1 M4.2	40% of the flooring materials is sustainable 80% of the flooring materials is sustainable	1 2
M5	Material	Roofing	Rate of roofing materials that is sustainable	* Rapidly renewable materials (grown and harvested within 10 years) * Reusable materials * Materials with at least 10% recycled pre-consumer components or 5% post-consumer recycled components * Autoclave materials	M5.1 M5.2	40% of the roofing materials is sustainable 80% of the roofing materials is sustainable	1 2
H4	Limiting VOC emissions	Paint and Overlay	Choose products with low VOC emissions	* Being recognized as a product with low VOC level (Green label, ISO) * Having a VOC level lower than the prescribed level of Vietnamese Standards	H4	50% of the material with a low VOC level	1

3.3. Analytical Results and Discussion

The proposed model seeks to maximize the number of material-related green building scores by fulfilling the Lotus requirements. Table 5 summarizes the optimization results that indicate the optimal percentage of each material type (i.e., x_{ij} column) for each building component. Table 5 shows that the building can reach a score of 13 in which the percentage of material of the Cm_1, Cm_2, Cm_3 were 35%, 41%, and 24%, respectively.

Table 5. Materials ratio after optimization.

Category	Symbols	x_{ij}	z_j	Category	Symbols	x_{ij}	z_j
	St_1	30%			Br_1	24%	
	St_2	69%		M2	Br_2	13%	3
	St_3	1%			Br_3	52%	
	Cm_1	35%			Br_4	11%	
M1	Cm_2	41%	3		Fl_1	99%	
	Cm_3	24%			Fl_2	1%	
	Br_1	21%		M4	Fl_3	0%	2
	Br_2	47%			GS_1	79%	
	Br_3	15%			GS_2	21%	
	Br_4	18%		M5	T_1	70%	2
	Gl_1	40%			T_2	30%	
	Gl_2	31%					
	Gl_3	17%			P_1	21%	
M3	Gl_4	12%	2				
	W_1	61%		H4	P_2	26%	1
	W_2	37%					
	W_3	0%			P_3	1%	
	W_4	1%			P_4	51%	
Lotus score (A)				**13**			
Total project cost ($)				**5,537,826**			
Total labor-working days				**8135**			

In order to provide decision-makers with more information in their material selections, a set of score scenarios was presented in Table 6 in which the Lotus score varied from 7 to 12 and total labor-working days and building cost were changed accordingly. Table 6 shows the optimal solution with the best materials, as well as the extent of their use on a case-by-case basis. It is easy to realize that when the constraint conditions are adjusted, the main structural materials of the building, such as steel, cement, and bricks, have the biggest changes in the selection process of materials, as they are materials that account for a large proportion of construction work in Vietnam. These materials greatly affect the cost as well as the construction time; therefore, changing only one Lotus score for these materials also significantly affects the construction cost and project completion time.

In contrast, in the non-structural wall category, the changing of types of sustainable bricks has the most impact on the Lotus score in comparison with all other remaining materials. Bricks are the first material to be changed when the Lotus score fluctuates, because until they meet the sustainability criteria, the proportions of materials in the other categories change to ensure the achievement of the targeted Lotus score. In contrast, in the non-structural wall category, the changing of types of sustainable bricks has the most impact on the Lotus score in comparison to all remaining materials.

Table 6. Optimal proportion of materials in each scenario.

	Lotus score: 12 points (B)			Lotus score: 11 points (C)			Lotus score: 10 points (D)		
	Total cost: $5,531,654			Total cost: $5,530,665			Total cost: $5,520,122		
	Total labor-working days: 8096			Total labor-working days: 8080			Total labor-working days: 8064		
Category	**Symbols**	x_{ij}	z_j	**Symbols**	x_{ij}	z_j	**Symbols**	x_{ij}	z_j
M1	St_1	30%	3	St_1	30%	3	St_1	30%	3
	St_2	70%		St_2	70%		St_2	70%	
	St_3	1%		St_3	1%		St_3	1%	
	Cm_1	35%		Cm_1	35%		Cm_1	35%	
	Cm_2	41%		Cm_2	41%		Cm_2	41%	
	Cm_3	24%		Cm_3	24%		Cm_3	24%	
	Br_1	21%		Br_1	21%		Br_1	21%	
	Br_2	47%		Br_2	47%		Br_2	47%	
	Br_3	15%		Br_3	15%		Br_3	15%	
	Br_4	18%		Br_4	18%		Br_4	18%	
M2	Br_1	50%	2	Br_1	59%	1	Br_1	79%	0
	Br_2	18%		Br_2	28%		Br_2	5%	
	Br_3	22%		Br_3	6%		Br_3	9%	
	Br_4	10%		Br_4	7%		Br_4	7%	
M3	Gl_1	40%	2	Gl_1	40%	2	Gl_1	40%	2
	Gl_2	31%		Gl_2	31%		Gl_2	31%	
	Gl_3	17%		Gl_3	17%		Gl_3	17%	
	Gl_4	12%		Gl_4	12%		Gl_4	12%	
	W_1	61%		W_1	61%		W_1	61%	
	W_2	37%		W_2	37%		W_2	37%	
	W_3	0%		W_3	0%		W_3	0%	
	W_4	1%		W_4	1%		W_4	1%	
M4	Fl_1	99%	2	Fl_1	99%	2	Fl_1	99%	2
	Fl_2	1%		Fl_2	1%		Fl_2	1%	
	Fl_3	0%		Fl_3	0%		Fl_3	0%	
	GS_1	79%		GS_1	79%		GS_1	79%	
	GS_2	21%		GS_2	21%		GS_2	21%	
M5	T_1	70%	2	T_1	70%	2	T_1	70%	2
	T_2	30%		T_2	30%		T_2	30%	
H4	P_1	21%	1	P_1	21%	1	P_1	21%	1
	P_2	26%		P_2	26%		P_2	26%	
	P_3	1%		P_3	1%		P_3	1%	
	P_4	51%		P_4	51%		P_4	51%	
	Lotus score: 9 points (E)			**Lotus score: 8 points (F)**			**Lotus score: 7 points (G)**		
	Total cost: $5,516,463			**Total cost: $5,514,052**			**Total cost: $5,513,011**		
	Total labor-working days: 8055			**Total labor-working days: 8016**			**Total labor-working days: 8013**		
Category	**Symbols**	x_{ij}	z_j	**Symbols**	x_{ij}	z_j	**Symbols**	x_{ij}	z_j
M1	St_1	30%	3	St_1	30%	3	St_1	30%	3
	St_2	70%		St_2	70%		St_2	70%	
	St_3	1%		St_3	1%		St_3	1%	
	Cm_1	35%		Cm_1	35%		Cm_1	35%	
	Cm_2	41%		Cm_2	41%		Cm_2	41%	
	Cm_3	24%		Cm_3	24%		Cm_3	24%	
	Br_1	21%		Br_1	21%		Br_1	21%	
	Br_2	47%		Br_2	47%		Br_2	47%	
	Br_3	15%		Br_3	15%		Br_3	15%	
	Br_4	18%		Br_4	18%		Br_4	18%	
M2	Br_1	79%	0	Br_1	79%	**0**	Br_1	79%	0
	Br_2	5%		Br_2	5%		Br_2	5%	
	Br_3	9%		Br_3	9%		Br_3	9%	
	Br_4	7%		Br_4	7%		Br_4	7%	

Table 6. *Cont.*

	Lotus score: 9 points (E)			Lotus score: 8 points (F)			Lotus score: 7 points (G)		
	Total cost: $5,516,463			Total cost: $5,514,052			Total cost: $5,513,011		
	Total labor-working days: 8055			Total labor-working days: 8016			Total labor-working days: 8013		
Category	**Symbols**	x_{ij}	z_j	**Symbols**	x_{ij}	z_j	**Symbols**	x_{ij}	z_j
M3	Gl_1 Gl_2 Gl_3 Gl_4 W_1 W_2 W_3 W_4	40% 31% 17% 12% 61% 37% 0% 1%	2	Gl_1 Gl_2 Gl_3 Gl_4 W_1 W_2 W_3 W_4	40% 31% 17% 12% 61% 37% 0% 1%	2	Gl_1 Gl_2 Gl_3 Gl_4 W_1 W_2 W_3 W_4	40% 31% 17% 12% 61% 37% 0% 1%	2
M4	Fl_1 Fl_2 Fl_3 GS_1 GS_2	99% 1% 0% 79% 21%	2	Fl_1 Fl_2 Fl_3 GS_1 GS_2	99% 1% 0% 99% 1%	1	Fl_1 Fl_2 Fl_3 GS_1 GS_2	99% 1% 0% 99% 1%	1
M5	T_1 T_2	93% 7%	1	T_1 T_2	93% 7%	1	T_1 T_2	100% 0%	0
H4	P_1 P_2 P_3 P_4	21% 26% 1% 51%	1	P_1 P_2 P_3 P_4	21% 26% 1% 51%	1	P_1 P_2 P_3 P_4	21% 26% 1% 51%	1

The correlation among the Lotus score and the project cost and the total labor-working days is shown in Figure 7. Points A–G illustrate the opportunity to obtain a Lotus score with the lowest budget and the lowest number of the total labor-working days. In addition, Figure 7 reveals that in order to achieve a higher Lotus score, more budget should be used, and the total labor-working days must be larger. However, in order to examine the correlation among them, each specific pair should be analyzed; these results are presented in Figures 8 and 9.

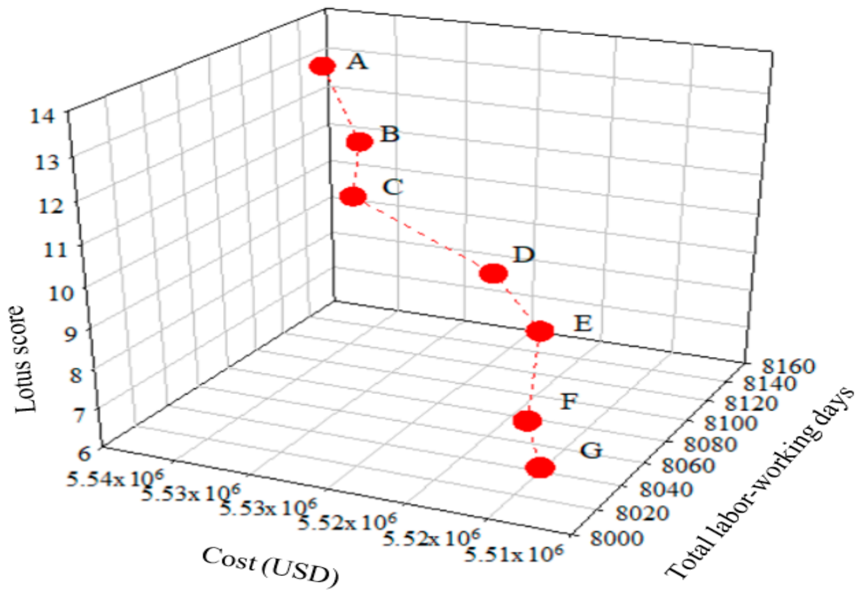

Figure 7. Correlation between Lotus points and project cost and total labor-working days.

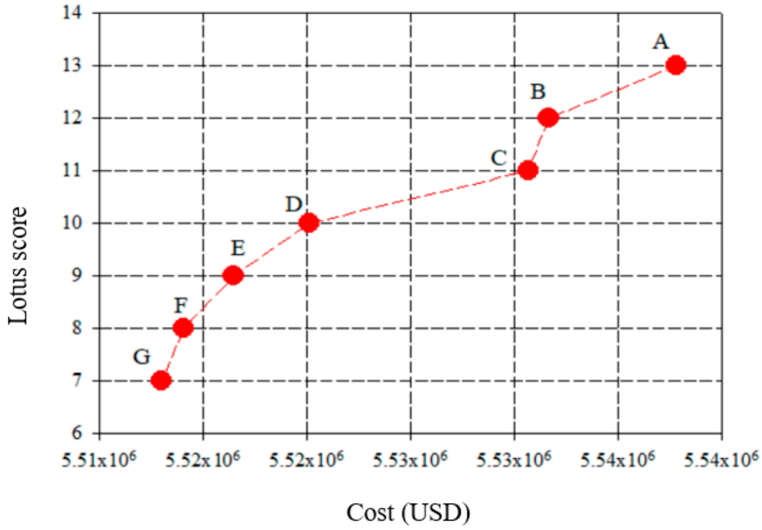

Figure 8. Correlation between Lotus score and cost.

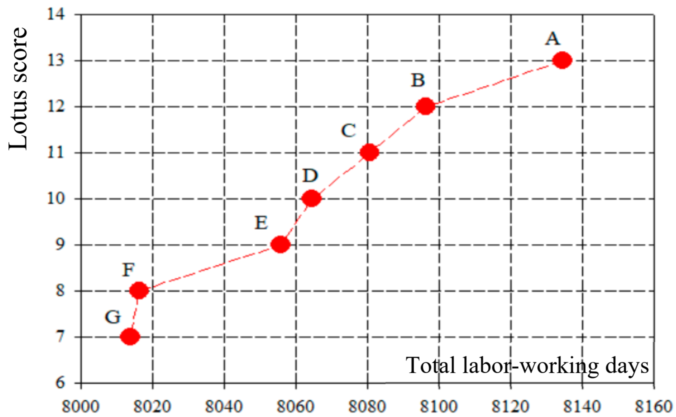

Figure 9. Correlation between Lotus score and total labor-working days.

As shown in Figure 8, the project can achieve Lotus scores of 7, 8, and 9 with a budget ranging from \$5,513,011 to \$5,516,463; to obtain a score of 10, a budget at \$5,520,122 is required, with a difference of \$3000–\$4000 to achieve a higher score. However, to increase from a score of 10 to scores of 11, 12, and the highest score of 13, the budget must be increased by \$10,000 for each Lotus score, with the amount of money at \$252,708; \$257,537, and \$263,229, respectively. Obviously, to obtain a higher score with an increase of 1–2 points, the cost increases from \$5000 to \$6000. This is a relatively large sum just for the cost of materials.

In Figure 9, a tendency that can be seen is that to achieve a higher Lotus score, greater total labor-working days must be employed. Based on the change of total labor-working days for each Lotus point, the selection of sustainable materials also affects the construction strategy, the construction methods, and the construction technology. For instance, by using sustainable materials and applying new construction technology, employees may be unfamiliar with the operation and construction process. Therefore, labor productivity may significantly reduce.

As shown in Figure 10, the change of Lotus score is recorded according to the corresponding costs and the total labor-working days. The results show that sustainable materials are more expensive and the labor workforce for construction must be more. This allows investors to consider and select materials from suppliers that supply the same category of materials to achieve their goals under budget constraints, along with the total labor required.

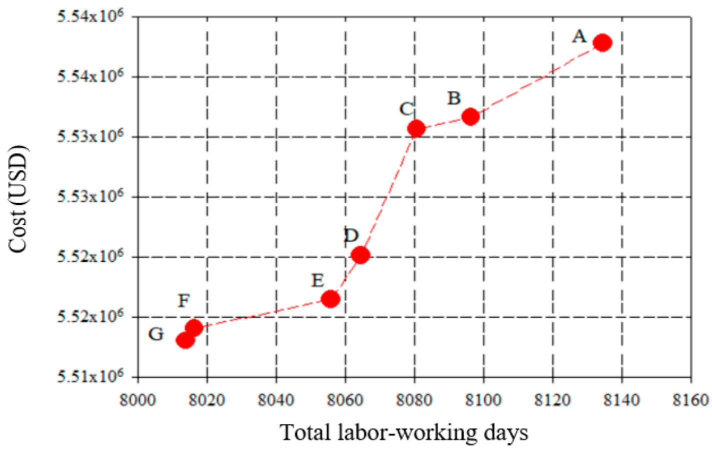

Figure 10. Correlation between total labor-working days and construction costs.

4. Conclusions

In any process of choosing sustainable materials for building construction, the decision is not easy, and it is often difficult to choose the best construction strategy. This is further complicated by the simultaneous consideration of project budgets, total labor-working days, and green building certification. In order to address this problem, the model in the study proposed an optimal model to select the rate of eco-friendly materials that achieved a minimum initial investment cost and total labor-working days, which is different from traditional design, and could maximize the score of construction project via Lotus-based system at the conceptual stage of building projects. Optimization results facilitates decision-makers to obtain a detailed material procurement plan. This will provide decision-makers with blueprints to improve the green performance of construction projects.

This study aims to build an eco-friendly material selection integrated platform that will enable building owners and designers to optimize decision making through knowledge of materials type, construction strategy, and Lotus-based green building certification system in Vietnam. The results of an experimental building in Danang city, Vietnam confirmed the importance of the materials that form the main structures of the building including bricks, cement, and steel. They are materials that account for a large proportion of the construction works in Vietnam. Therefore, an adjustment of the proportion of these materials is greatly affecting the Lotus green building scores, project cost, and completion time of the project. Hence, this study suggests that if stakeholders in the project aim to adjust the sustainable goals for the building, they should not adjust the materials in this category; instead, they should adjust the materials of non-structural walls, particularly considering different types of eco-friendly bricks. This suggestion is consistent with the construction works in Danang city because bricks are still the main materials used in dividing spaces in buildings.

At the same time, with increasing awareness of sustainable construction in Vietnam, eco-friendly bricks (e.g., adobe bricks and foam concrete bricks) are being produced at lower and lower costs. This will help stakeholders to easily change the proportion of bricks in the building when they want to change sustainability goals via Lotus score, while the cost and time of construction will not be remarkably affected. The research results also show the importance of the specifications of sustainable materials on the market, because without these parameters, it will be a great challenge to evaluate sustainable buildings based on the Lotus standards. Therefore, state management agencies need to adopt specific regulations to ensure that manufacturers provide data or information about the composition of materials to help investors, private units, consultants, and construction units to choose materials that ensure the sustainability of buildings. In summary, the proposed model based on multi-objective optimization approach provides a guidance for decision-makers in selecting approximate materials for buildings toward sustainability.

The challenge for increasing the use of eco-friendly construction materials in developing countries is that each material is managed individually by different manufacturers, making it difficult for building owners, designers, and construction companies to access detailed information about the types, prices, standards, and environmental impacts of products certified as green building materials. Future work should include the advanced model based on a Web-based platform that could collate data easily to modify the established optimization model. Moreover, if a client can easily employ a program by utilizing only the limited information available during initial construction planning, accessibility can also be improved for users aiming to achieve green building certification.

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