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Decision-Making Framework for Sustainable Construction Products Selection in SMEs

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Abstract: In the construction industry, decision-making plays an important role in achieving sustainability. Decision-making processes have significantly expanded to consider detailed product information when selecting sustainable alternatives in order to make more accurate choices; however, it has also turned out to be a barrier due to the knowledge intensiveness of the process and unreliable product information, especially in SMEs (small and medium-sized enterprises). This research focuses on developing a simple decision-making framework for selecting sustainable products as alternatives. The proposed framework is developed with analysis of two transparent factors: (1) life cycle cost and (2) technology growth rate. A decision-making model also provides a visual comparison of the alternatives in consideration with quadrant model. The resulting framework provides a distinct anticipated outcome description for each product considered; thus, enabling the decision-makers to identify and choose the most suitable alternative. The framework is expected to influence the spread of sustainable products in SMEs.

Keywords: sustainable products; decision framework; obsolescence; life cycle cost; SMEs

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1. Introduction

The construction industry can play an important role in building a sustainable environment on our planet. The construction industry has shown considerable influence on a number of global environmental issues. These include: 23% of all air quality pollution; 50% of CFC (Chlorofluorocarbons) gas production; 40% of water pollution; 50% of landfill waste generation; 50% of ozone depletion; 80% of agricultural land loss; 50% of coral reef destruction; and 25% of rainforest destruction [1]. The products used in construction projects also cause a significant portion of these impacts. As reported by Hamner [2], around three billion tons of raw materials are used annually to manufacture building products worldwide, which is 40–50% of the total material flow in the global economy. To address this issue, sustainable products are produced as alternatives to almost all the products used in the construction industry [3]. Sustainable products are those products that generate greater positive or lower negative social, environmental, and economic impacts along the value chain from producer to end-user than conventional products [4].

Although adopting sustainable products in the construction industry is identified as the easiest way to achieve sustainable development [5], the selection of sustainable products as alternatives has been found to be one of the most difficult tasks in the construction industry [6]. Recent research suggests that one of the most important the factors affecting the selection of sustainable materials is the perception of the extra costs that may be incurred; meanwhile costs are dealt with by lifecycle costing (LCC) approaches and the initial investments are being compensated for in the long run by savings and returns. In addition, the lack of sustainable material information is another of the main barriers to sustainable material selection [7]. The LEED (Leadership in Energy and Environmental Design) certification program encourages and accelerates the adoption of sustainable products across building projects, and there are over 460 environmental labels worldwide regarding sustainability [8]. Nevertheless, reports show that only 6% of EU citizens completely trust producers' claims about their products' environmental performance [9]. The lack of sustainable material information and the reliability of the information that is being provided is a major setback for decision-makers to select a sustainable product as an alternative [5–7,10–13]. This kind of reliability issue exists because most of these labels are developed by third-party organizations, such as NGOs (Non-Governmental Organization), or by the collaboration of different organizations with little or no government involvement in the labeling processes. With global sustainability standards still under development, there is a major concern for the reliability of these data. This raises the issue of the data transparency provided by the seller, in terms of being able to cross-verify the data. The uncertainties existing with products of this kind require evaluation to achieve realistic and transparent results of the product [14], but time and budget constraints hinder the testing of new products and systems before application [15], especially in SMEs [16]. In a developing nation such as India, the distribution of Small and Medium Enterprises (SMEs) in the construction industry is around 30,000 small-scale firms, 500 medium scale firms, and 120,000 unregistered contractors compared to 250 large firms [17]. Similarly, among the enterprises in the European Union (EU), 99 percent of them are considered SMEs and they contribute to 70 percent of industrial pollution in the UK alone [16]. To summarize, the rapid growth of the product market and the lack of global standards for sustainable products have affected the reliability of the factors used in decision considerations of construction company. Additionally, added features and considerations of factors from "cradle to grave" of sustainable products have significantly increased the complexity of product selection methods, in comparison with the traditionally used methods.

As an effort to address this issue, a simple decision-making framework that considers transparent factors for choosing sustainable products as alternatives is developed. The applicability of the framework is expected to influence the global spread of sustainable products in all scales of construction projects, which is otherwise prevented by the negative perceptions and difficulties in decision making. The research focuses on identifying the least number of quantifiable factors that are collectively homogeneous to each individual product while being sufficiently reliable to make decisions. Using these factors, a decision-making model that provides a visual comparison of each alternative, and a description of the state of each alternative, is developed within the framework. The preliminary study helps to understand sustainable products and various decision methods that have been introduced to choose the alternatives. Additionally, this step provides information to select the criteria, factors, and processes that align with the research objective. The second step includes the developed decision-making framework and its process description. This step includes the description of criteria, factors, and the methods to calculate the factors, and then the steps involved in how the factors are substituted in the model, followed by the model and its significance. The third step includes an applicability study of the framework, and a case study as validation of the framework, followed by discussions, and then the conclusion.

2. Sustainable Products and Decision Methods

According to UNESCO (United Nations Educational, Scientific and Cultural Organization), sustainability is a paradigm for thinking about the future in which environmental, societal, and economic considerations are balanced in the pursuit of improved quality of life; meanwhile, the processes and pathways to achieve sustainability are referred to as sustainable development. The selection of sustainable products is one such process to achieve sustainability. To understand the potential of the influence of sustainable products in the construction industry, compare the fact that being a developed country, half of the US building stock required by 2050 has yet to be built, with the condition of developing countries, where over 80% of the global population lives [2]. According to the Leadership in Energy and Environmental Design (LEED), the green building process so far uses environmentally friendly materials that can save 350 metric tons of CO_2 emissions annually [18]. This provides a glimpse into the sustainable future of our planet with the help of replacing all non-sustainable products with sustainable products. Unlike green products, the sustainable products used in the construction industry are hard to define objectively. One of the reasons is that sustainability considers the impacts on economic and social aspects, along with environmental aspects, while green production focuses on the environmental aspects of products. Green products are defined as products that contain recycled materials, reduce waste, conserve energy or water, use less packaging, and/or reduce the amount of toxins disposed or consumed [19]. Although generalized, the research follows the definition of sustainable products by Borregaard [4], who defined sustainable products as those products that generate greater positive or lower negative social, environmental, and economic impacts than do conventional products, along the value chain from producer to end-user.

Previous studies on the selection of sustainable products are studied to understand the selection process of sustainable products and the methods used (Table 1).

Table 1. Previous Studies on decision-making for Sustainable Products.

Author	Decision for	Method Used	Evaluation Criteria/ Factors	Scope	Observations
Arroyo et al. [20]; Parrish et al. [21]; Grant [22]; Nguyen et al. [23]	Sustainable Alternatives	Choosing by Advantage (CBA)	Product /component/system specific	Comprehensive/undefined	Data intensive
Dangana et al. [14]	Sustainable technology for retail buildings	Multi-Criteria Decision Analysis (MCDA)	Value Tree Developed	Limited/well defined	Simplified and transparent
Akadiri et al. [24]	Sustainable materials for building projects	Fuzzy extended AHP (FEAHP)	Sustainable Triple bottom line based (TBL)	Comprehensive/well defined	Knowledge intensive
Lounis et al. [25]	Sustainable and resilient infrastructures	Risk-Informed Decision Making	Product /component/system specific	Comprehensive/undefined	Knowledge and data intensive
Piotr et al. [26]	Renewable/ Sustainable Energy Systems	Borland Delphi	Product /component/system specific	Limited/well defined	Data intensive
Hossaini et al. [27]	Sustainable Materials	Energy-Based Life Cycle Analysis (Em-LCA)	Product /component/system specific	Comprehensive/undefined	Knowledge and data intensive
Govindan et al. [28]	Sustainable Materials	DNAP [1] and TOPSIS [2]	Product /component/system specific	Comprehensive/undefined	Knowledge and data intensive
Lippiatt [29]	Green building products	LCA [3] and LCC	Product /component/system specific	Comprehensive/well defined	Knowledge and data intensive

[1] Decision-making Trial and Evaluation Laboratory (DEMATEL) and analytic network process (ANP); [2] Techniques for order preference by similarity to an ideal solution; [3] Life Cycle Assessment.

The studies included multiple decision-making methods that promised to provide highly accurate decisions. Lifecycle Assessment (LCA) [27,29] is one such method, but detailed LCA is critically dependent on high volumes of product-specific data, and is often unaffordable [30]. Similarly, the DNAP-TOPSIS [28] and Risk-Informed Decision-making [25] methods also require detailed knowledge and extensive data to make decisions. Additionally, hybrid methodologies, such as Fuzzy extended AHP [24], require knowledge of specific software tools to perform. Multicriteria Decision Analysis (MCDA) [14] methods are proven to provide simplified and transparent decisions to choose sustainable products. Choosing by Advantages (CBA) is one such MCDA method that has a very basic, but promising, logic of choosing the products based on the number of advantages, in the case of having reliable data. Lastly, the Borland Delphi method by Piotr et al. [26] shows that a minimalistic amount of support from modern software technologies could yield promising decisions. However, 'the lack of comprehensive tools to compare material alternatives' remains an important barrier affecting the selection of sustainable products in building projects [7,31–33]. Previous research has either provided decision methods for generalized sustainable product categories or product-specific methods. The generalized methods bring into question the effectiveness of such methods for all of the products in scope, whereas the product-specific methods demand knowledge of multiple methods/criteria to cover a comprehensive set of products.

3. Framework Development

By combining the knowledge gained from the preliminary study, a decision-making framework was developed. Firstly, the decision criteria and the factors addressing the decision criteria were established. Then, the decision-making framework was created. Finally, the decision model that will be within the framework was developed.

3.1. Decision Criteria—Economic Value, Obsolescence and Risk

To choose suitable alternatives from sets of both sustainable and conventional products, suitable decision criteria that are specific to sustainable products were identified from the preliminary studies performed. These criteria were selected through the literature review based on their importance relevant to the decision-makers in SMEs, and the current market situation of the sustainable products was taken into consideration.

3.1.1. Economic Value

The cost of sustainable products is the most frequently cited barrier affecting the selection and use of sustainable materials [7], as even the perception of the extra cost being incurred is one of the most important barriers that affect the selection of sustainable materials [13,32,34,35]. Considering that cost is the most important criterion, it is required to be justified in terms of the economic value of the product from purchase to disposal/resale.

3.1.2. Obsolescence

Obsolescence occurs when products become "out of use" or "out of date" [36]. A study on demands for private sector housing refurbishment concluded that obsolescence, rather than deterioration, was found to be an overwhelmingly important basis for refurbishment [37]. The direct effect of product obsolescence is the tremendous amount of waste it generates [36].

Obsolescence has been comprehensively addressed in the defense, aerospace, electronics, and software sectors in over 60 research articles, and with over 15 obsolescence management tools (Rojo et al., 2010) [38], but not much consideration has been given in the construction industry, where the effect of obsolescence has, until recent times, been relatively low, which correlates with the concern about the amount of waste generated by the construction industry. The sustainability perspective of the industry now needs to consider obsolescence as a decision criterion to uphold sustainability [39–42].

3.1.3. Risk

Risk of "newness" is the risk of not meeting the technical requirements for performance or quality of output under the conditions of operation [43]; thus, either directly or indirectly affecting the economy and safety of the stakeholders. New products experience frequent malfunctions that should have been resolved before they were released into global markets [44]. As observed in the aerospace, automobile, electronics, and software industries, this risk of "infant mortality" in new products has increased in the construction industry in the sustainable product market. Sustainable products are more prone to risk in comparison with conventional products, with respect to the newness of the product being available in the market [12]. The criteria under consideration have certain interdependencies, such as the obsolescence and risk of a product affecting the disposal/resale costs and maintenance costs of the product, respectively, enabling them to be a balanced set of criteria on which to base a decision.

3.2. Factors Addressing Decision Criteria

3.2.1. Lifecycle Cost (LCC)

LCC is used to address economic value, as it considers all the relevant economic factors, both in terms of initial capital cost and future operation costs [45–48]. Lifecycle Cost here considers all the costs involved from the decision maker's perspective, which includes the initial/capital cost of the product, through to the disposal/resale cost of the product. For example, selecting a highly energy-efficient HVAC system over a conventional HVAC system incurs a high initial cost, but considering the lifecycle cost of the system proves that the energy efficient alternative has a better economic value over the other. So, having LCC as the factor for economic value provides better justification, in terms of the expenses incurred over the entire lifetime of the products. The LCC of a product is dependent on the local cost indices, as the calculation of future costs, including operation and maintenance costs, is calculated based on local cost data. This helps to provide a more accurate region-specific comparison of products.

The Lifecycle Cost of the product is estimated by using the following formula (Equation (1)), which is adopted and simplified from Soni et al. [49]:

$$\mathrm{LCC} = \mathrm{C}_0 + \mathrm{PV}\ (\mathrm{C}_1 + \mathrm{C}_2 + \mathrm{C}_3 + \mathrm{C}_4 - \mathrm{C}_5), \tag{1}$$

where

C_0 is the Initial capital cost;
PV is the Present value;
C_1 is the Lifetime operating cost;
C_2 is the Lifetime maintenance cost;
C_3 is the Capital rehabilitation cost;
C_4 is the Disposal cost;
C_5 is the residual value.

Considering the exclusive lifetime of the products [14] from the building itself, costs, such as operation cost and maintenance cost, are calculated specific to the product lifecycle, but are repeated to meet the period of the building lifecycle or minimum required lifespan.

While the LCC formula is constantly evolving to consider various criteria specific to products and facilities, their impact among others is taken into consideration [48]; to provide an LCC value based on data that are reliable, and with the least processing knowledge, the fundamental version of LCC calculation was selected to be used in the framework.

3.2.2. Technology Growth Rate (TGR)

TGR is the factor that addresses obsolescence and risk. The growth rate of a product technology affects the chances of the product being obsolete [50,51] and the uncertainty that comes with the product because of its "newness" [44,52]. The technology growth rate addressed here is the growth rate of the most advanced feature of the product specific to the company, starting from the introduction of the product to the market. For example, consider window panels incorporated with transparent solar cells, which are relatively new in the market. Existing window panel features and the capacity of power generation in these transparent solar cells are increasing exponentially with the rapid growth of technology in the field. This leads to the product available in the market today becoming obsolete within a short period. Similarly, because of the newness of such products, the risk of performance failure is high. The TGR of a product is an independent company-specific factor that provides a rational perspective of reputation specific to the product lineup, and not to the brand as a whole.

The technology growth rate of the most significant feature of the product is calculated by XY scattered plot of "feature vs. time", inspired by the obsolescence risk assessment of computer components provided by Josais et al. [53]. The TGR value is extracted using the exponential trendline function equation in Excel (Equation (2)):

$$\mathrm{Y} = \mathrm{c} * \mathrm{e} \hat{\ } \mathrm{b} * \mathrm{x}, \tag{2}$$

where

Y is the performance of the significant feature of the product considered;
c is the Initial performance value of the feature;
e is the Exponential coefficient;

b is the Technology growth rate;
x is Time.

The technology growth rate (b) of the product is obtained from the equation in decimal form and converted into a percentage. In the case of a newly released product in the market, the TGR value will be assumed and computed in the model as 100%.

The exponential growth rate function in Microsoft Excel is used in finance to calculate the alteration in currency value, stock value, and so on. Using it to calculate the growth rate of a product's performance over a period is a simple alternative to other methods of growth rate calculations.

3.3. Framework Workflow

Figure 1 shows the framework workflow that was developed for this research, which is based on the framework provided by Pearce et al. [54] for the selection of sustainable materials. The process involved identifying the purpose of design elements, and then preparing performance criteria to fulfill the design purpose. Then, a number of possible alternatives that fulfill the criteria were selected. All the infeasible alternatives, due to various reasons, such as design limitations, application limitations, and others, were pruned, prior to the next set of evaluations. The few shortlisted alternates were then evaluated to find their LCC and technology growth rate values.

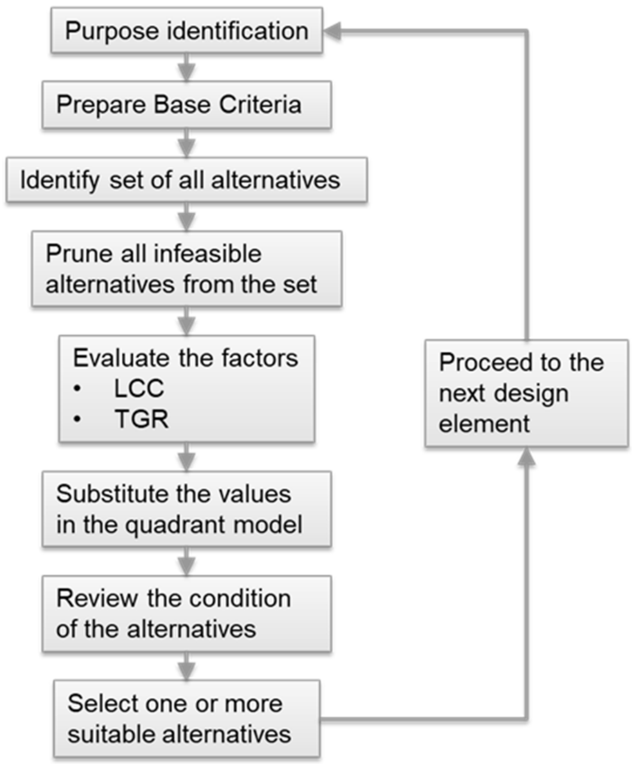

Figure 1. Framework Workflow.

3.4. Decision-Making Model

A four-quadrant decision-making model was developed within the framework that provided a visual comparison of all the alternatives based on LCC and TGR values that are relative to one another. The description of the model and the significance of each quadrant were established. The visual aid of the model was expected to play a major role when comparing multiple products, and to reason out with owners and investors, especially those who lack professional knowledge on product selection.

Description—The Four-quadrant model consists of LCC on the y-axis, and TGR on the x-axis, as shown in Figure 2. The base value (point of intersection of axis) is the mean value of the LCC and TGR of all the alternatives. The values of LCC and TGR of each alternative are substituted in the four-quadrant model, with reference to the base value. The values of LCC are given in the range of high to low, and the values of the TGR—being rates—are given in the range of incremental to rapid, for a better understanding of the model.

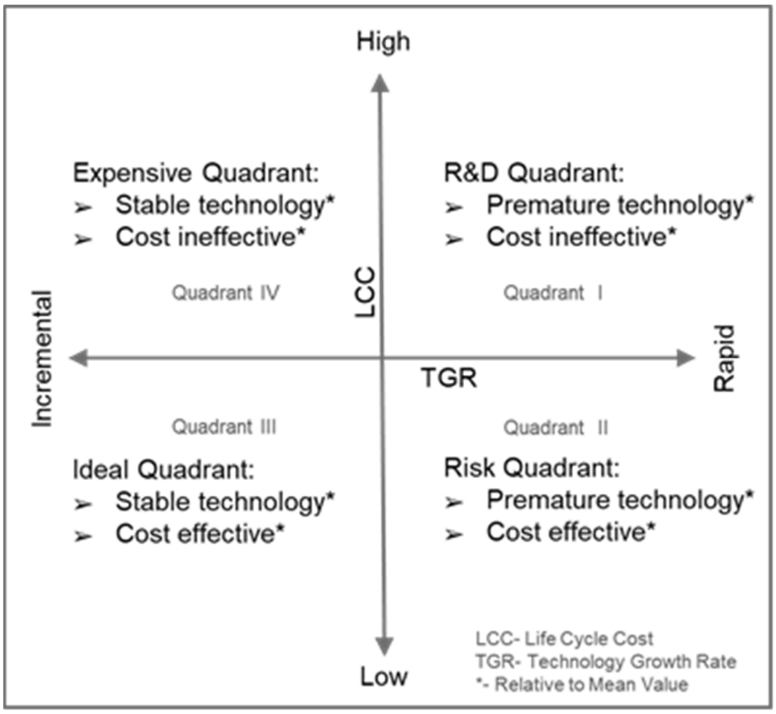

Figure 2. Four Quadrant Decision Model.

Quadrant significance–The 'R&D Quadrant' has products with high LCC and rapid technology growth rate similar to prototypes that require further research and testing before implementation. The quadrant emphasizes that sustainability cannot be achieved by compromising on the economic value and safety of the end-users. Moreover, product obsolescence generates more waste, and so the products in this quadrant are not recommended. The 'Risk Quadrant' has products that provide LCC savings in the long run, using the latest technology available. Since these are prone to more risk and obsolescence relative to common practice, products in this quadrant are recommended in partial combination and with a frequent inspection. The 'Ideal Quadrant' has products with cost-saving and mature technology that are ideal to implement, and are highly recommended. The 'Expensive Quadrant' has sustainable products that are expensive at times, even with a stable growth rate, due to the expenses of the manufacturing process, and the expense of the materials used in the products, among others. Products with mature technology with relatively little or no economic value, are recommended only for the requirements of regulation and certification.

4. Application

To examine the working of the model, and to understand its applicability in the industry, two case studies were performed to identify issues and limitations of the model, and to compare the methods currently used in the industry with the model.

4.1. Case Study 1

A simulated example of decision-making to choose roof tiles for a new single-family house was tested. Table 2 below shows the details of the sample project.

Table 2. Sample Project Characteristics.

Project Characteristics	Description
Location	San Diego, California, USA
Project Type	Single-Family House
Area	245 square meters (US Average as of 2016) [1]
Stakeholders	Owner, Architect, LEED Professional and General Contractor
Product	Roof Tiles/Shingles
[2] Roof Area	319 square meter (average for 39.81° roof slope)
Available solar energy	1900 kW/kW-yr. (California-Average)
Climate	Mild and sunny weather throughout the year

[1] National Association of Home Builders Discusses Economics and Housing Policy; [2] http://www.calculator.net/roofing-calculator, accessed on 1 September 2022.

To provide sustainable solutions, the project characteristics were given importance to choose the most suitable option. In this case, the roof area exposed to sunlight and the average solar energy availability were important characteristics to include products that offered solar energy production features. Similarly, the product durability standards needed to be based on the local climatic conditions, as expensive, high standard, and multiple featured products are not always the best choices.

After the assessment of the project characteristics, the selection process was followed according to the framework developed. The design element to install was the roof tiles/shingles, and the purpose that was identified was to provide sustainable weather protection. Based on this purpose, and with due consideration given to the project characteristics, a set of performance criteria were set as the conditions to be met before further review. Table 3 shows the products that were shortlisted through this pruning method. Among twenty-one options considered initially, fourteen were pruned, based on the base performance criteria, and then three more were pruned due to the lack of historical data. This process brought the number of alternatives down to four. Then, the complete specifications of the shortlisted products were collected from the product sources without prejudice. The technology growth rate of each product's significant feature was calculated, and the lifecycle cost of each product was calculated using the local cost data standards, and computed in the model.

Table 3. Decision-making Workflow based on the Proposed Framework.

Purpose	Sustainable Weather Protection (Particularly Heat Insulation)
Base Criteria	1. At least one sustainable feature • Renewable energy generation, (LEED: 1–2, 1–3 Points) [1] • Made from recycled materials, (LEED: 2–4 Points) [1] • 100% recyclability, (LEED: 1 Points) [1] • Energy-saving by insulation (LEED: 1–2 Points) [1] 2. 39.81° roof slope 3. Fire Resistant • Best in Class Fire rating, equivalent to Class A UL 790 [2] 4. Warranty • Functional warranty > 20 yrs. • Product warranty > 30 yrs.
Total no. of products considered	21
Shortlisted based on Base criteria	7
Shortlisted due to historical information shortage	4

[1] http://www.usgbc.org/, accessed on 1 September 2022; [2] http://library.ul.com/, accessed on 1 September 2022.

As shown in Tables 4 and 5, the LCC and the TGR values were calculated using the formulae proposed for four alternatives, and then computed into the quadrant model (Figure 3). The following were inferred from the framework application: Company 1 provided the recommended roofing option, balancing cost-effectiveness, and stable technology relative to the other three options. Company 3 provided the second-best option. Company 2 could have been an option when LEED certification was required, in the absence of products from Company 1 or Company 3. Company 4 provided the most economical option, but was recommended only to be partially implemented with high caution and increased inspection frequency, as it was considered to have a higher risk, being a new product on the market.

Table 4. LCC Calculation for Case Study 1.

Alternatives	Company 1	Company 2	Company 3	Company 4
Product Name	Slate	Single width Slate	Roof Slate	Solar Roof
C_0	USD 27,440	USD 30,870	USD 38,141.6	USD 69,594
C_1	-	-	-	−USD 98,900 *
C_2	USD 16,464	USD 18,522	USD 22,884	USD 41,756.4
C_3	-	-	-	-
C_4	USD 13,720	USD 13,720	USD 13,720	USD 13,720
C_5	−USD 10,976	-	USD 15,256	-
LCC	USD 46,648	USD 63,112	USD 59,489.6	USD 26,170.4

* Information provided by the company

Table 5. TGR Calculation for Case Study 1.

Alternatives	Company 1	Company 2	Company 3	Company 4
Product Name	Slate	Single width Slate	Roof Slate	Solar Roof
Product's date of introduction	2013	1997	1988	2017
Criteria	Recycled materials used	Fire Rating	Recycled materials used	Recycled materials used
Current functionality value of criteria	25%	Class A	100%	Undisclosed
TGR	0%	0%	0%	100%

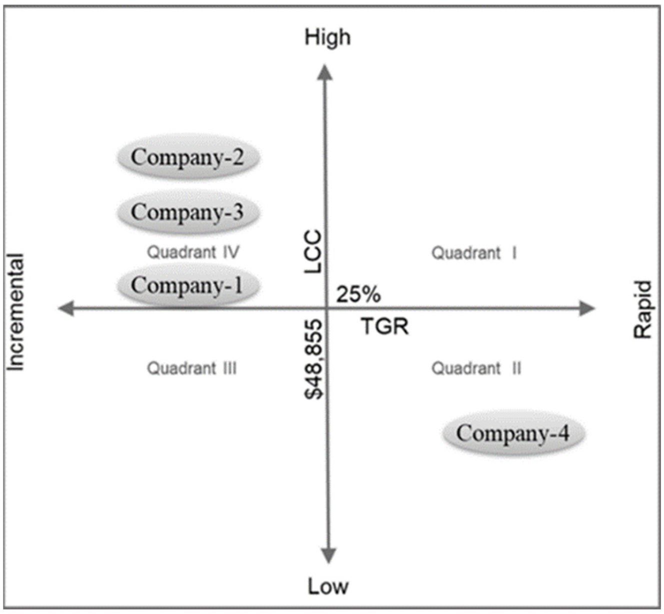

Figure 3. Quadrant Model for Case Study 1.

4.2. Case Study 2

Another case study was performed to compare the framework with existing selection processes in the industry. The case study involved the renovation of lighting fixtures for the car-parking facility of a multistory building. The study is part of a major renovation performed by a major facility management firm in South Korea. The purpose identified was to provide sustainable lighting solutions to obtain green certification. The number of alternatives was brought down to two options, 'Alternative A' and 'Alternative B'.

Alternative A was to continue with the existing lighting products (replacing with the same new ones). Alternative B was to replace with highly energy-efficient LED lights. The choice of the company providing the LED option was based on the reputation of the company selling the product. The decision process included the calculation of two quantities, the LCC and CO_2 emission value (Table 6) of the products.

Table 6. Case Study 2-Existing Decision Criteria Calculations.

Characteristics of Alternative B over Alternative A	Values
Annual power savings	475,698 kWh/year
Estimated amount of annual power savings	50,900 USD/year
Recovery period for return on investment	3.59 year
Reduction rate compared to power usage as of 2016	1.45%
Estimated annual reduction rate of greenhouse gas emissions by power reduction	54.25%

The facility management chose 'Alternative B' based on the LCC cost advantage over 'Alternative A'. Even though the capital cost of the LED lighting option was over 177,000 USD, the application of the product accounted for over 45,000 USD in energy savings per year, enabling the company to reach the break-even point of the investment in 3.59 years. Although the carbon emission value was calculated, the decision was made solely based on the lifecycle cost of the product. The carbon emission value calculated was only used to acquire sustainable certification.

The LCC was calculated based on an assumed forecast of the product to be used in the facility (Table 7). And the TGR was calculated based on the functionality value of each alternative, light intensity and energy saving, respectively (Table 8). Figure 4 shows the result of the proposed method, and provides a visual comparison between the two alternatives in terms of LCC and TGR. The relative gap between the LCC of each alternative is significantly small in comparison with the gap between their TGR. The model recommendations such as 'Alternative B' should be chosen with caution, in partial combination and with increased inspection frequency. In comparison, 'Alternative A' is relatively very stable, and close to the base LCC value, making it the recommended choice, and green certification efforts can be directed to other parts of the renovation work.

Table 7. LCC Calculation for Case Study 2.

Specs\Alternatives	Alternative A	Alternative B
Product Name	fluorescent lighting	LED lighting
C_0	38,615 USD	182,937 USD
C_1	884,566 USD	629,860 USD
C_2	-	-
C_3	115,844 USD	182,931 USD
C_4	-	-
C_5	-	-
LCC	1,039,025 USD	995,733 USD

Table 8. TGR Calculations for Case Study 2.

Specs\Alternatives	Alternative A	Alternative B
Product Name	fluorescent lighting	LED lighting
Product's Date of introduction	2007	2017
Criteria	Light intensity/unit power	New smart dimming energy saving
Current functionality value of Criteria	65.45 Lm/W	-
TGR	0	100%

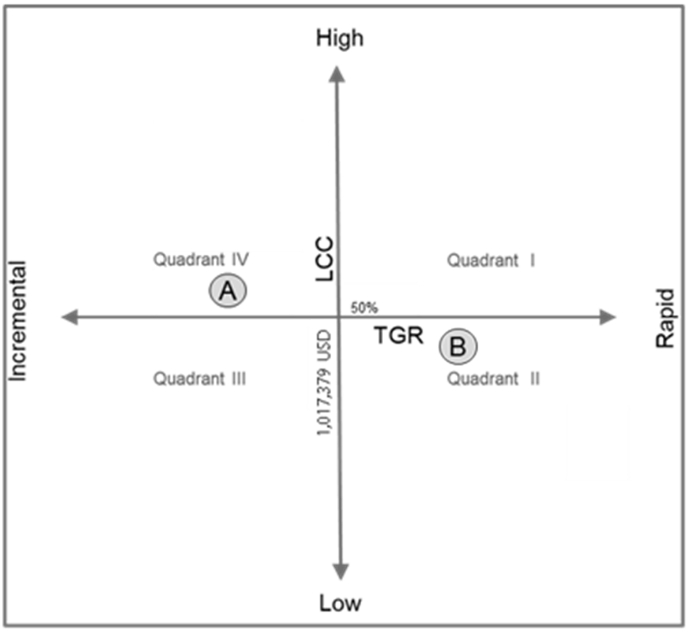

Figure 4. Quadrant Model for Case Study 2.

5. Discussions

To enable sellers to place their products in the ideal quadrant relative to their competitors, it is important to provide products that are mature and last for a long period concerning their technology and product quality. Moreover, the sustainability factor of the products must also reflect their economic value. For example, an environmentally friendly product that compromises on cost efficiency over its competitors cannot be sustainable, as the triple bottom line rule for sustainability is social, economic, and environmental value. The comparison of the proposed framework with existing methods shows similarities, such as LCC being used as a decision-making tool for product selection even in large-scale firms. However, the LCC was only considered by the facility management until the return of investment was achieved, which appeared to show that the LED lighting option had a significant cost advantage, which, considering it as a long-term investment, was a small difference in reality. The professionals consider the reputation of the brand, whereas the current study considers the reputation of the product in terms of the performance criteria. In this case, although the company providing the LED solution was reputable, the product selected here had a relatively new feature from the company, making it more susceptible to risk and obsolescence. It was also observed that significant advancement is more easily visible with products that contribute to energy saving/energy generation. This is due to rapid technological growth in electrical and electronic products and relatively gradual growth with the performance of other products. Apart from the visual advantage over the existing methods, the model developed provides important insights into the relations between the alternatives, which are supportive to the decision-makers to make rational decisions. Additionally, the visual comparison is expected to help with better communication between owners and contractors to agree upon the right product.

The application result shows that the historical data of an individual company's construction products are progressively developing, but are not readily available. The lack of linear data of products is also due to naming and introducing an advanced version of the same product into an entirely new line of products. Additionally, LCC is calculated based on rate assumptions, and on standard local construction cost index values for maintenance costs, operation costs, and residual and disposal values, and not product-specific values. These limitations to the framework can be resolved by better profiling the product lineup and providing public records of all the versions of the same product released since entering the market.

Even though most modern methods of decision-making are dependent on extensive data, they also require additional knowledge about various sustainable products, software, and product evaluation methods, ideally increasing the complexity to make decisions from numerous new decision criteria [14]. This prevents the construction industry from adopting green practices, especially in developing nations such as India [55]. A major threat causing this is that small and medium contractors do not have the wherewithal to upgrade their capability [17], which leads to a condition called knowledge gap between the large, medium, and small-scale firms. The knowledge gap hypothesis explains that knowledge, in the same way as other forms of wealth, is often differentially distributed throughout a social system [56]. The knowledge gap in this context refers to the difference in knowledge regarding various sustainable products, software, and product evaluation methods between different scales of the industry. It is important to consider this knowledge gap to provide solutions to make decisions. This increased complexity thus prevents the spread of sustainable products, especially in SMEs, due to the growing knowledge gap. Therefore, to enable the spread of sustainable products, especially in SMEs, it is important to provide a decision-making framework that demands little knowledge of the products and processes, while using reliable factors. Unlike existing methods that depend on the liability of the specifications for decision making, this method considers the growth of performance of a significant feature of the product. This also limits the scope of the framework to nonstructural sustainable products. Structural and nonstructural sustainable products face similar challenges for decision-making from comparing their barriers to implementation from Griffen et al. [57] and Akadiri [7]; however, the failure of structural sustainable products to perform their intended function directly affects the integrity of the structure, whereas that of nonstructural products is more indirect, and can be mitigated by repair or replacement of the product. Considering the intensity of the risk involved, structural sustainable products are recommended to be chosen upon detailed evaluation using methods such as Risk-Informed Decision Making provided by Lounis et al. [25]. Structural sustainable products are products that become or are part of the structural system [57]. Meanwhile, Singh et al. [52] explained that nonstructural products are the fixtures, attachments, and items in buildings and structures that are not designed as load-bearing elements. By combining the earlier definitions of the sustainable product by Borregaard [4] and the definition of nonstructural products, nonstructural sustainable products can be defined as sustainable products that become, or are, part of a nonstructural component in buildings and structures. Nonstructural sustainable products include architectural features, such as exterior cladding and glazing, ornamentation, ceilings, interior partitions, and stairs; mechanical components and systems, including air-conditioning equipment, ducts, elevators, escalators, pumps, and emergency generators; electrical components, including transformers, switchgear, motor control centers, lighting, and raceways; fire protection systems, including piping and tanks; and plumbing systems and components, including piping, fixtures, and equipment [58].

6. Conclusions

Reliability of data and lack of knowledge are two of the most important barriers preventing the spread of sustainable products in the construction industry. Existing decision methods depend on these data, and demand knowledge of the products and the decision methods to make decisions. A simple decision-making framework considering transparent factors is developed addressing the criteria of economic value, risks, and obsolescence. The developed framework's application is examined through an application study, and its issues and limitations were identified. Further, a case study on the framework's application was performed and compared with the existing method used in the industry, for a better understanding of the application potential of the framework. Considering that the possible end-users of the proposed framework are professionals and decision-makers, specifically in SMEs, the simple decision-making framework can support selection of sustainable products by reducing the efforts of collecting information with low reliability. Using only two factors can be seen as an advantage of the results of this study as well as a limitation of this study; thus, in addition to LCC and TGR, the sustainable product selection decision can affect various management areas including design complexity, construction on site, and maintenance strategy. In this aspect, the scope of this research is specific to non-structural sustainable products rather than structural sustainable products or materials, which can have more correlation with design and construction of the facility. If these issues are addressed, the applicability of the framework is expected to influence the global spread of sustainable products in all scales of construction projects, which is otherwise prevented by the negative perceptions and difficulties in decision making. The beneficiaries of the framework are the owners, construction professionals, and the public, as the framework is anticipated to decrease the purchase of premature products released in the market, by enabling the decision-makers to foresee the necessary avoidance of purchasing such products.

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References

1. Hawken, P.; Lovins, A.B.; Lovins, L.H.; Lovins, A.B.; Lovins, L.H. *Natural Capitalism: The Next Industrial Revolution*; Routledge: London, UK, 2013; ISBN 978-1-134-03306-5.
2. Hamner, B. Effects of Green Purchasing Strategies on Supplier Behaviour. In *Greening the Supply Chain*; Sarkis, J., Ed.; Springer: London, UK, 2006; pp. 25–37. ISBN 978-1-84628-299-7.
3. Spiegel, R.; Meadows, D. *Green Building Materials: A Guide to Product Selection and Specification*; John Wiley & Sons: Hoboken, NJ, USA, 2010; ISBN 978-0-470-88055-5.
4. Borregaard, N. *Challenging Preconceptions about Trade in Sustainable Products: Towards Win-Win for Developing Countries*; IIED: London, UK, 2005; ISBN 978-1-84369-581-3.
5. Akadiri, P.O.; Olomolaiye, P.O. Development of sustainable assessment criteria for building materials selection. *Eng. Constr. Archit. Manag.* **2012**, *19*, 666–687. [CrossRef]
6. Kibert, C.J. *Sustainable Construction: Green Building Design and Delivery*; John Wiley & Sons: Hoboken, NJ, USA, 2016; ISBN 978-1-119-05517-4.
7. Akadiri, P.O. Understanding barriers affecting the selection of sustainable materials in building projects. *J. Build. Eng.* **2015**, *4*, 86–93. [CrossRef]
8. Ecolabel Index. Available online: http://www.ecolabelindex.com/ (accessed on 29 October 2018).
9. Eurobarometer, F. *Europeans' Attitudes towards the Issue of Sustainable Consumption and Production*; Directorate-General for Communication: Brussel, Belgium, July 2009; Volume 256, pp. 1–8.
10. Kang, M.Y.; Guerin, D.A. The state of environmentally sustainable interior design practice. *Am. J. Environ. Sci.* **2009**, *5*, 179–186. [CrossRef]
11. Lerma, B.; Giorgi, C.D.; Allione, C. *Design and Materials. Sensory Perception Sustainability Project: Sensory Perception Sustainability Project*; FrancoAngeli: Milan, Italy, 2013; ISBN 978-88-204-6239-0.
12. Rao, P.B.; Pavan, B. Role of Contractors in Green Industrial Projects—An overview of difficulties challenged in green documentation. *Int. J. Emerg. Technol. Adv. Eng.* **2013**, *3*, 69–74.
13. Williams, K.; Dair, C. What is stopping sustainable building in England? Barriers experienced by stakeholders in delivering sustainable developments. *Sustain. Dev.* **2007**, *15*, 135–147. [CrossRef]
14. Dangana, Z.; Pan, W.; Goodhew, S. *Delivering Sustainable Buildings in Retail Construction*; Association of Researchers in Construction Management (ARCOM): Edinburgh, UK, 2012; ISBN 978-0-9552390-6-9.
15. Beliz, O.; Kutluhan, O.; Sevilay, D. Investigating the Components of Innovation in Construction Projects. *J. Manag. Eng.* **2016**, *32*, 04015052. [CrossRef]
16. Moore, S.B.; Manring, S.L. Strategy development in small and medium sized enterprises for sustainability and increased value creation. *J. Clean. Prod.* **2009**, *17*, 276–282. [CrossRef]

17. NSDC. *Human Resources and Skill Requirements in the Building Construction and Real Estate Sector*; National Skill Development Corporation: New Delhi, India, 2017.
18. Green Building and Climate Change | U.S. Green Building Council. Available online: https://www.usgbc.org/articles/green-building-and-climate-change (accessed on 29 October 2018).
19. Nimse, P.; Vijayan, A.; Kumar, A.; Varadarajan, C. A review of green product databases. *Environ. Prog.* **2007**, *26*, 131–137. [CrossRef]
20. Arroyo, P.; Tommelein, I.D.; Ballard, G. Deciding a Sustainable Alternative by 'Choosing by Advantages' in The Aec Industry. In Proceedings of the 20th Annual Conference of the International Group for Lean Construction, San Diego, CA, USA, 18–20 July 2012.
21. Parrish, K.; Tommelein, I. Making design decisions using choosing by advantages. In Proceedings of the IGLC17: 17th Annual Conference of the International Group for Lean Construction, Taipei, Taiwan, 15–17 July 2009; pp. 501–510.
22. Grant, E.J.; Jones, J.R. A Decision-making Framework for Vegetated Roofing System Selection. *J. Green Build.* **2008**, *3*, 138–153. [CrossRef]
23. Nguyen, H.V.; Lostuvali, B.; Tommelein, I.D. Decision analysis using virtual first-run study of a viscous damping wall system. In Proceedings of the 17th Annual Conference of the International Group for Lean Construction (IGLC 17), Taipei, Taiwan, 15–17 July 2009.
24. Akadiri, P.O.; Olomolaiye, P.O.; Chinyio, E.A. Multi-criteria evaluation model for the selection of sustainable materials for building projects. *Autom. Constr.* **2013**, *30*, 113–125. [CrossRef]
25. Lounis, Z.; McAllister, T.P. Risk-Based Decision Making for Sustainable and Resilient Infrastructure Systems. *J. Struct. Eng.* **2016**, *142*, F4016005. [CrossRef]
26. Rosinski, P.; Brady, L.; Cotgrave, A.; Al-Shamma'a, A. Decision Making Aid for Selection of Renewable/Sustainable Energy Systems for Buildings. In Proceedings of the International Conference on Sustainable Design and Construction (ICSDC), Kansas City, MI, USA, 23–25 March 2011. [CrossRef]
27. Hossaini, N.; Hewage, K. Sustainable Materials Selection for Canadian Construction Industry: An Emergy-Based Life-Cycle Analysis (Em-LCA) of Conventional and LEED Suggested Construction Materials. *J. Sustain. Dev.* **2011**, *5*, 2. [CrossRef]
28. Govindan, K.; Madan Shankar, K.; Kannan, D. Sustainable material selection for construction industry—A hybrid multi criteria decision making approach. *Renew. Sustain. Energy Rev.* **2016**, *55*, 1274–1288. [CrossRef]
29. Lippiatt Barbara, C. Selecting Cost-Effective Green Building Products: BEES Approach. *J. Constr. Eng. Manag.* **1999**, *125*, 448–455. [CrossRef]
30. Srinivas, K.; Amaresh, C. Development of a Method for Estimating Uncertainty in Evaluation of environmental Impacts during Design. In Proceedings of the ICED 2007, the 16th International Conference on Engineering Design, Paris, France, 28–31 July 2007.
31. AlWaer, K. Building sustainability assessment methods. *Proc. Inst. Civ. Eng. Eng. Sustain.* **2012**, *165*, 241–253. [CrossRef]
32. Bond, S. Barriers and drivers to green buildings in Australia and New Zealand. *J. Prop. Investig. Financ.* **2011**, *29*, 494–509. [CrossRef]
33. Ikediashi, D.I.; Ogunlana, S.O.; Oladokun, M.G.; Adewuyi, T. Assessing the level of commitment and barriers to sustainable facilities management practice: A case of Nigeria. *Int. J. Sustain. Built Environ.* **2012**, *1*, 167–176. [CrossRef]
34. Sustainability and Interior Design | Sustainable Design | Green Building. Available online: https://www.scribd.com/document/7687294/sustainability-and-interior-design (accessed on 29 October 2018).
35. Samari, M.; Ghodrati, N.; Esmaeilifar, R.; Olfat, P.; Shafiei, M.W.M. The Investigation of the Barriers in Developing Green Building in Malaysia. *Mod. Appl. Sci.* **2013**, *7*, 1. [CrossRef]
36. Rai, R.; Terpenny, J. Principles for Managing Technological Product Obsolescence. *IEEE Trans. Compon. Packag. Technol.* **2008**, *31*, 880–889. [CrossRef]
37. Aikivuori, A. Periods and demand for private sector housing refurbishment. *Constr. Manag. Econ.* **1996**, *14*, 3–12. [CrossRef]
38. Romero Rojo, F.J.; Roy, R.; Shehab, E. Obsolescence management for long-life contracts: State of the art and future trends. *Int. J. Adv. Manuf. Technol.* **2010**, *49*, 1235–1250. [CrossRef]
39. Ofori, G. Developing the Construction Industry in Ghana: The case for a central agency. *Concept Pap. Prep. Improv. Constr. Ind. Ghana Natl. Univ. Singap.* **2012**, *13*, 3–18.
40. Doloi, H. Understanding impacts of time and cost related construction risks on operational performance of PPP projects. *Int. J. Strateg. Prop. Manag.* **2012**, *16*, 316–337. [CrossRef]
41. Doherty, J.M. A Survey of Computer Use in the New Zealand Building and Construction Industry. *J. Inf. Technol. Constr.* **1997**, *2*, 73–86.
42. Vanegas, J.A.; DuBose, J.R.; Pearce, A.R. *Sustainable Technologies for the Building Construction Industry*; Georgia Institute of Technology: Atlanta, GA, USA, 1996.
43. Tatum, C.B. Managing for Increased Design and Construction Innovation. *J. Manag. Eng.* **1989**, *5*, 385–399. [CrossRef]
44. Makhlouf, A.S.H.; Aliofkhazraei, M. *Handbook of Materials Failure Analysis with Case Studies from the Aerospace and Automotive Industries*; Butterworth-Heinemann: Oxford, UK, 2015; ISBN 978-0-12-801177-5.
45. Norman, G. Life cycle costing. *Prop. Manag.* **1990**, *8*, 344–356. [CrossRef]
46. Kirk, S.J.; Dell'isola, A.J. *Life Cycle Costing for Design Professionals, 2nd Revised Edition*; McGraw-Hill Companies: New York, NY, USA, 1995; ISBN 978-0-07-034804-2.

47. Woodward, D.G. Life cycle costing—Theory, information acquisition and application. *Int. J. Proj. Manag.* **1997**, *15*, 335–344. [CrossRef]
48. Gluch, P.; Baumann, H. The life cycle costing (LCC) approach: A conceptual discussion of its usefulness for environmental decision-making. *Build. Environ.* **2004**, *39*, 571–580. [CrossRef]
49. Soni, V.; Dash, A.P.; Singh, S.P.; Banwet, D.K. Life Cycle Costing Analysis of Energy Options: In Search of Better Decisions towards Sustainability in Indian Power & Energy Sector. *Glob. J. Manag. Bus. Res.* **2014**, *14*.
50. Bartels, B.; Ermel, U.; Sandborn, P.; Pecht, M.G. *Strategies to the Prediction, Mitigation and Management of Product Obsolescence*; John Wiley & Sons: Hoboken, NJ, USA, 2012; ISBN 978-1-118-27546-7.
51. Cooper, T. *Longer Lasting Products: Alternatives to the Throwaway Society*; CRC Press: Boca Raton, FL, USA, 2016; ISBN 978-1-317-10354-7.
52. Kali Charan, A.K.; Singh, R. *Risk and Innovation—Case for Building a Methodology Tool to Assist Informed Decision Making for Managers*; Social Science Research Network: Rochester, NY, USA, 2006.
53. Josias, C.; Terpenny, J.P.; Mclean, K.J. Component obsolescence risk assessment. In Proceedings of the 2004 Industrial Engineering Research Conference (IERC), Houston, TX, USA, 16–19 May 2004; pp. 15–19.
54. Pearce, A.R.; Hastak, M.; Vanegas, J.A. A decision support system for construction materials selection using sustainability as a criterion. In Proceedings of the NCSBCS Conference on Building Codes and Standards, Albuquerque, NM, USA, 1–2 November 1995; pp. 1–4.
55. M-Brain Market & Media Intelligence Solutions, Knowledge Gap Hinders India Construction Industry's Progress in Going Green. Available online: https://www.m-brain.com/insights/industries/construction-property-development/knowledge-gap-hinders-india-construction-industrys-progress-in-going-green/ (accessed on 1 September 2022).
56. Schumann, D.W.; Thorson, E.E. *Internet Advertising Theory and Research*; Lawrence Erlbaum Associates Publishers: Mahwah, NJ, USA, 2007; ISBN 978-0-8058-5109-0.
57. Griffin, C.; Knowles, C.; Theodoropoulos, C.; Allen, J.H. Barriers to the implementation of sustainable structural materials in green buildings. In Proceedings of the Structures and Architecture, 1st International Conference on Structures and Architecture ICSA, Guimaraes, Portugal, 21–23 July 2010; pp. 1349–1357. [CrossRef]
58. Gillengerten, J.D. Design of Nonstructural Systems and Components. In *The Seismic Design Handbook*; Naeim, F., Ed.; Springer: Boston, MA, USA, 2001; pp. 681–721. ISBN 978-1-4615-1693-4.