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Development of an Effective System for Selecting Construction Materials for Sustainable Residential Housing in Western Australia

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Abstract

Urbanization and living comfort have revolutionized the construction industry. Many techniques and strategies have been used to improve the overall efficiency of construction and to reduce waste during and after the construction activity; some are cost effective and some not. Sustainable construction strategies have addressed these issues by proposing relatively more cost effective and environment-saving solutions. One strategy is to select sustainable construction materials at the building design stage. This article involved a questionnaire survey to collect data about local technical stakeholders' (architects, designers, engineers, estimators, and managers) awareness of environmental sustainability and current practices for selecting construction materials. A sustainability index (SI) was developed using SPSS (Statistical Package for the Social Sciences) for the complex statistical analysis. These data were used to develop a decision support system (DSS) using the multi-criteria decision making (MCDM) technique, the TOPSIS. The support system was validated by applying it to sustainable roof products in a pilot case study—these materials are frequently used in local markets for residential construction in West Australia. So the main objective was to get insight to local market trends and features involved in construction materials selection. Data analysis was carried out to develop a decision support system to help technical stakeholders in construction materials selection process.

Keywords

Construction Industry, Sustainability Index (SI), Multi-Criteria Decision Making (MCDM), Decision Support System (DSS), TOPSIS

1. Introduction

In the past the global construction industry has developed rapidly in terms of advanced technology and the incorporation of safety and sustainability. Similarly, the Australian construction industry now considers sustainability as a vital factor for maintaining a balance in preservation and consumption of natural resources. To investigate the local trends and general procedures in the selection process for materials in residential building construction, a questionnaire survey was developed and circulated among the leading construction companies in Western Australia.

Survey response rate and validity: Data were collected in three survey formats: postal, online, and self-administered surveys. A total number of 52 survey questionnaires were sent to construction companies with a cover letter and a form for participant consent. From these, 11 responses were received (response rate = 21.15%; Figure 1). This response rate was considered adequate because other researchers in the construction industry also reported response rates for postal surveys between 20% and 30% [1] [2] [3].

For the online surveys, 35 company representatives were sent a uniform resource locator (URL) link to access the survey and record their responses. The response rate was 48.57% (17 responses). Face-to-face, self-administered surveys were also conducted with 7 company representatives (23 companies sent request; 30.43% response rate). This method of data collection is considered the best; complete responses are received through this method. All survey responses were evaluated before analysis to verify that all questions were answered; missing values were adjusted in the analysis with SPSS (Statistical Package for the Social Sciences, (version 24)). Some irrational responses and suggestions were received but most responses were relevant based upon the work experience of the respondents.

We used a Likert scale in our survey, which is considered reliable to investigate the overall perceptions and experiences of a group of relatively homogeneous

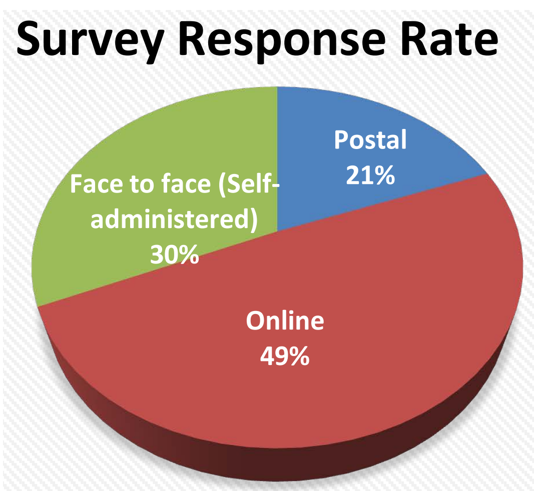

Figure 1. Survey response rate.

individuals of similar backgrounds and trades [4]. Using a multi-criteria decision making (MCDM) technique, we processed the data to develop a sustainability index (SI) for ranking the most appropriate and sustainable building construction materials. The system was validated by running a pilot analysis on local sustainable roofing materials from two major material suppliers.

Margin of error: For an inferential statistical analysis, researchers agree a sample size (n) of more than 30 is required to obtain an accurate value [5] [6] [7] [8]. Prior research validated that minimum threshold value to rank a data acceptable is 30. We got the response from more than 30 construction firms, hence our sample size ($n = 36$) is acceptable for statistical analysis with the appropriate analysis tool to get acceptable and reliable results.

2. Statistical Data Analysis

SPSS (Statistical Package for the Social Sciences, version 24) was used to analyze the data. Frequencies, percentages, averages were calculated. All values are used for open-ended questions. Data were collected on the organization profiles (*i.e.* type, size, and age of organization; area of building projects, focus, and main client type) to obtain overall snapshots of the organizations.

2.1. Level of Awareness of Environmental Issues

All company representatives and technical stakeholders were somewhat aware of environmental parameters, but only 33.34% of the 36 were extremely aware. Almost 20% were only slightly aware; most of these respondents had a trade background, with no higher education degree in construction (**Table 1**).

Considering environmental issues at the conceptual design stage

A large body of literature describes the importance of addressing environmental issues at the first step in the construction process, the conceptual design stage [9] [10]. To investigate the degree of agreement or disagreement regarding this practice, respondents were asked "Is it important to consider the environmental issues at the conceptual stages?" A seven-point Likert scale recorded their viewpoint (1 = *Strongly disagree*, 7 = *Strongly agree*); the extended Likert scale was used to canvass the full spectrum of opinions and current general practice in the local market (**Table 2**).

Table 1. Level of awareness of environmental issues in building construction.

Awareness scale	Frequency	Percent	Cumulative percent
Extremely aware	12	33.34	33.34
Moderately aware	8	22.23	55.57
Somewhat aware	9	25.0	80.57
Slightly aware	7	19.45	100.0
Total		100.0	

Source: Analysis of survey data (2018).

Table 2. Consideration of environmental issues at conceptual design stage.

Agreement scale	Frequency	Percent	Cumulative percent
Strongly disagree	0	0	0
Disagree	0	0	0
Somewhat disagree	0	0	0
Neutral	3	8.33	8.33
Somewhat agree	6	16.66	24.99
Agree	15	41.66	66.65
Strongly agree	12	33.33	100
Total		100	

Source: Analysis of survey data (2018).

Table 2 shows that most (about 75%) of the respondents (75%) agreed or strongly agreed that the best time to consider environmental or and sustainability issues is at the conceptual stage. Other researchers report similar findings as well [11]. Considering all these environmental and sustainability issues at the start of the process allows us to change our design accordingly, and the capital cost can be well managed and minimized.

2.2. Building Design Priorities

The analysis showed that the decision makers were aware of the importance of using environmentally friendly and sustainable construction materials. The respondents were asked to prioritize their objectives to gauge the level of importance they assigned to project objectives, including environmental impacts and sustainable construction materials (Table 3).

The following formula was used to calculate the values in Table 3:

$$\mathrm{RI} = \sum \frac{w}{A \times N} \tag{a}$$

where RI = relative index, w = weighting given by respondents (range 1 - 7), A = highest weight (*i.e.* 7), N = total number of respondents. The value of the relative index ranges from 0 to 1.

The respondents' highest priority was to satisfy the client's specifications (Table 3), which indicates that most of the time efforts are made to reduce the cost as well.

3. Sustainability Considerations

The implementation of sustainability depends upon the knowledge and awareness of technical stakeholders (e.g. architects, designers, engineers, estimators, and managers).

Although the respondents stated they were aware of sustainability and its importance in construction, 52.77% had only an average knowledge of the sustainable products available in the market. Moreover, the proportion of respondents

Table 3. Ranking of project objectives.

Project Objective	Weighted total	RI	Rank	Mean Value
Satisfy Client Specifications	140	0.778	1	3.889
Meet Project Deadline	134	0.744	2	3.722
Meet Building Regulation	134	0.744	3	3.722
Sustainability Criteria	130	0.722	4	3.611
Environmental Impacts	126	0.700	5	3.500
Minimize the Cost	125	0.694	6	3.472

Source: Analysis of survey data 2018.

with poor knowledge (22.22%) exceeded the proportion with good knowledge (16.66%) (Table 4). Hence, the major stakeholders need to learn about sustainable products and their efficacy and adaptability. Most respondents thought that clients or their representatives are less concerned about this factor than about other considerations, and so they pay less attention to this issue. The small percentage of respondents with excellent knowledge (8.33%) all belonged to well-established, large organizations.

3.1. Sustainability Assessment

In contrast, most respondents (88.88%) agreed that it is important to select sustainable materials for building construction (Table 5); only one respondent (2.77%) provided any reasons for not doing so (cost and lack of skilled labor).

Despite the respondents' prior claim of knowing about sustainability and its importance, the analysis showed that the percentage of their projects in which sustainability was considered important was low (Table 6).

A majority of respondents (36%) completed projects without considering sustainability as an important factor for building construction, although implementing sustainability activities can give competitive advantage over rival firms that are reluctant to implement those activities [12].

3.2. Constraints in Selecting Sustainable Materials

The building industry uses large quantities of raw materials and energy in all stages from construction to operation. This means choosing materials with high content in embodied energy involve in high energy demand at construction stage and vice versa in operational phase [13] [14].

To gauge the real-world problems or obstacles faced by the technical stakeholders in selecting sustainable materials, respondents were asked to rank such issues on a 5-point Likert scale (1, *low*; 5, *high*). The degree of agreement, calculated as Kendall's W, was 0.248 (Table 7). This value indicates that almost all of the technical stakeholders face the same obstacles, with some exceptions.

The degree of agreement is calculated Kendall's W = 0.248 which shows almost all technical stakeholders are facing the same obstacles with some exceptions.

Table 4. Knowledge of sustainable design.

Knowledge Scale	Frequency	Percent	Valid Percent	Cumulative Percent
Excellent	3	8.33	8.33	8.33
Good	6	16.66	16.66	25
Average	19	52.77	52.77	77.76
Poor	8	22.22	22.22	100
Total		100	100	

Source: Analysis of survey data 2018.

Table 5. Importance of sustainable materials in building development.

Knowledge scale	Frequency	Percent	Valid Percent	Cumulative percent
Yes	32	88.88	88.88	88.88
No	3	8.33	8.33	97.21
If no, give reason	1	2.77	2.77	100
Total		100	100	

Source: Analysis of survey data (2018).

Table 6. Projects considering sustainability important.

Projects	Frequency	Percent	Cumulative Percent
<10%	13	36.11	36.11
10% - 20%	10	27.77	63.88
21% - 30%	5	13.88	77.76
31% - 40%	2	5.55	83.31
41% - 50%	4	11.11	94.42
>50%	2	5.55	100
Total		100	

Source: Analysis of survey data (2018).

Table 7. Constraints in sustainable material selection.

Stakeholder influence	RI[a]	Rank
Lack of information	0.73	2
Uncertainty in liability of work	0.67	7
Maintenance concern	0.73	3
Building code regulations	0.65	6
Lack of tools and data	0.70	5
Perception of extra cost being incurred	0.76	1
Perception of extra time being incurred	0.72	5
Perception that sustainable materials are low in quality	0.45	11
Aesthetically less pleasing	0.55	10

Continued

Project will be delayed	0.67	9
Limited suppliers	0.68	6
Low flexibility in alternatives	0.65	5
Unwilling to adopt the change	0.66	6
Kendall's W	(0.248)	

[a]Relative index. Source: Analysis of survey data (2018).

4. Development of Criteria for Sustainable Material Selection

The gap between information and implementation can be reduced by developing systems and IT features that are easy to use. This is a combined responsibility of all sectors involved in the construction industry. It is a mutual responsibility of government and the private sector to introduce and implement regulations for a "greener" and safer environment for future generations (Raynsford, 2000).

The criteria for sustainable material selection that were investigated were divided into three categories: environmental criteria, socio-economic criteria, and technical criteria (**Table 8**).

The respondents were asked to rank the sub-criteria for importance and the data were analyzed (**Table 9**).

Aesthetics was ranked first in the socio-economic category (RI = 0.88; **Table 9**). This criterion was designated as high importance as per our predefined values: all factors with an RI > 0.8 were considered of high importance and those with an RI < 0.8 considered of medium to high importance.

A decision model will help technical stakeholders to select from a wide range of options, either classical or innovative. We used the above sustainability criteria for computational analysis in order to formulate the best combination of alternative construction materials. Six major criteria were used (**Figure 2**). These 6 criteria were further divided into 23 sub-criteria (**Table 10**).

5. TOPSIS-Based Approach for Prioritized Aggregation

An aggregated MCDM environment means combining the values of a set of attributes to represent a single value for the entire set of attributes. Much work has been done to introduce the prioritization in aggregation method using the TOPSIS. The derivation of our MCDM model using this prioritization approach is described below.

A sustainability index framework basically helps the decision makers to integrate the issues of sustainability while selecting the available construction materials. Selecting sustainable construction materials from the pool of alternative sustainable materials is a time consuming and difficult practice. Applying the MCDM technique is the best method for integrating objective and subjective weights of various conflicting criteria in order to choose the most appropriate sustainable material. However, the process is challenging.

Table 8. Criteria for sustainable material selection for construction professionals.

Environmental criteria	Socio-economic criteria	Technical criteria
E1: Potential for reuse	S1: Disposal cost	T1: Maintainability
E2: Environmentally favorable disposal options	S2: Health and safety	T2: Buildability
E3: Air quality impacts	S3: Maintenance cost	T3: Resistance to decay
E4: Ozone depletion potential	S4: Aesthetics	T4: Fire resistance
E5: Environmental impact during manufacturing	S5: Use of local materials	T5: Life expectancy
E6: Less toxicity	S6: Capital cost	T6: Energy saving
E7: Regulatory compliance	S7: Skilled labor availability	
E8: Reduce pollution		
E9: Wastage in production		
E10: Raw materials extraction process		

Source: Analysis of survey data (2018).

Table 9. Ranking of criteria for sustainable material selection for construction professionals.

Performance criteria								Valid percentage
	Valid percentages of scores							
Environmental criteria	1	2	3	4	5	*RI*[a]	*Ranking*	*Importance*
E1: Potential for reuse	0.0	11.1	13.9	44.4	30.6	0.79	23	M-H[b]
E2: Environmentally favorable disposal options	2.8	8.3	27.8	30.6	30.6	0.72	17	M-H
E3: Air quality impacts	2.8	8.3	33.3	33.3	22.2	0.69	18	M-H
E4: Ozone depletion potential	5.6	8.3	41.7	16.7	27.8	0.76	15	M-H
E5: Environmental impact during manufacturing	2.8	13.9	33.3	19.4	30.6	0.67	13	M-H
E6: Less toxicity	2.8	11.1	30.6	25	30.6	0.86	7	H[c]
E7: Regulatory compliance	5.6	5.6	27.8	33.3	27.8	0.84	10	H
E8: Reduce pollution	0.0	5.6	19.4	50.0	25.0	0.85	5	H
E9: Wastage in production	4.4	15.4	31.9	37.4	11.0	0.79	20	M-H
E10: Raw materials extraction process	5.6	19.8	45.1	20.9	8.8	0.77	19	M-H
Socio-economic criteria								
S1: Disposal cost	2.8	8.3	16.7	44.4	27.8	0.78	21	M-H
S2: Health and safety	0.0	8.3	27.8	33.3	30.6	0.80	9	H
S3: Maintenance cost	0.0	5.6	22.2	38.9	33.3	0.81	8	H
S4: Aesthetics	0.0	5.6	36.1	36.1	22.2	0.88	1	H
S5: Use of local materials	0.0	8.3	33.3	41.7	16.7	0.76	16	M-H
S6: Capital cost	2.8	27.8	36.1	36.1	33.3	0.81	14	H
S7: Skilled labor availability	5.5	16.5	39.6	29.7	8.8	0.64	22	M-H
Technical criteria								
T1: Maintainability	0.0	5.6	27.8	44.4	22.2	0.86	2	H
T2: Buildability	0.0	0.0	9.9	53.8	36.3	0.85	6	H

Continued

T3: Resistance to decay	0.0	8.3	27.8	30.6	33.3	0.79	4	M-H
T4: Fire resistance	0.0	8.3	27.8	30.6	33.3	0.84	11	H
T5: Life expectancy	0.0	5.6	25.0	30.6	38.9	0.78	12	M-H
T6: Energy saving	0.0	2.8	38.9	30.6	27.8	0.84	3	H

[a]Relative index. [b]medium to high. [c]high. Source: Analysis of survey data (2018).

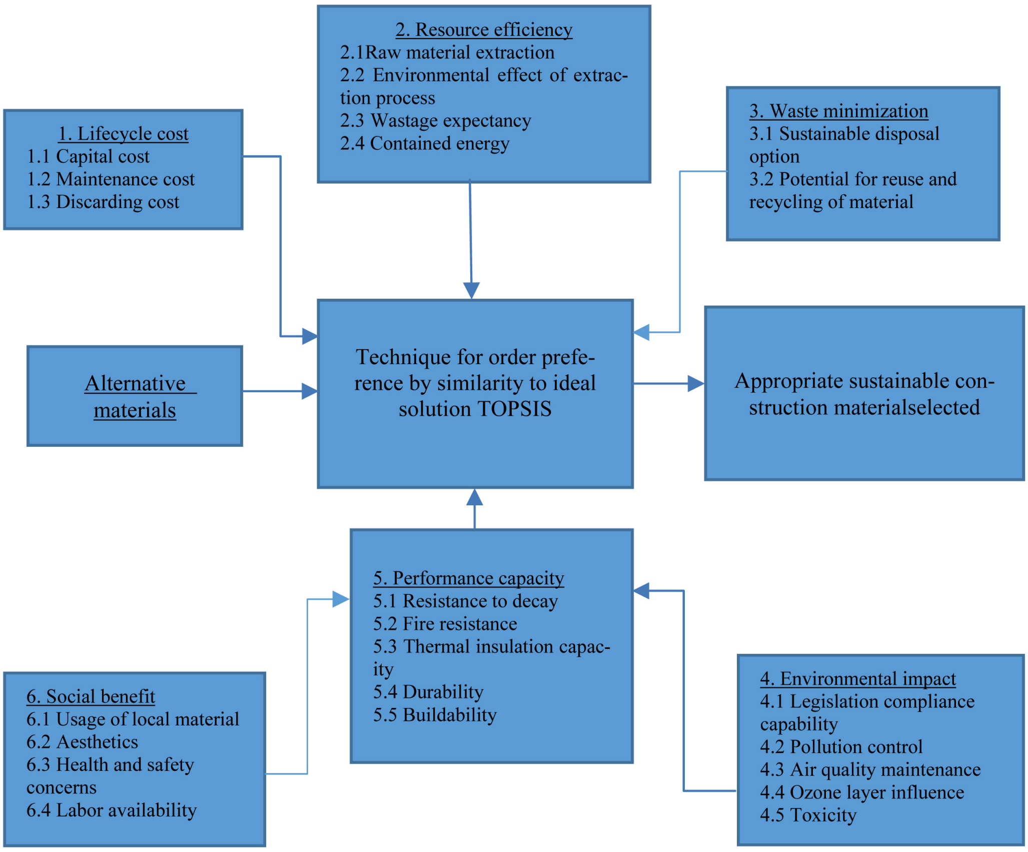

Figure 2. Conceptual framework for sustainable material selection.

The first step is to determine the most suitable aggregation method, usually from two major types: the crisp aggregation method, which is used to aggregate the real values; and the fuzzy aggregation method, which is used to aggregate the linguistic labels [15].

The second, most complicated, step is to define the boundary condition. The boundary condition compels the result of an aggregation function $f(x)$. The limit is defined as the minimal and maximal boundaries of possible output.

$$f(0,\cdots,0)=0 \text{ and } f(1,\cdots,1)=1, \text{ where } x\in[0,1] \tag{1}$$

The commutativity property states that ordering/ranking of arguments does not matter when there is equal importance or no relationship is considered among the different criteria.

$$f(x_1,x_2,\cdots,x_n)=f(x_2,x_1,\cdots,x_n)=f(x_n,x_2,x_1,\cdots),\quad x\in S \tag{2}$$

Table 10. Criteria and sub-criteria grouped with type.

Criteria	Sub-criteria	Description	Criteria & type
1. Life cycle cost	1.1 Capital cost	Initial purchasing cost of material	−C1
	1.2 Maintenance cost	Total repair cost during whole lifecycle of material	−C2
	1.3 Discarding cost	Demolition and disposal cost of material	−C3
2. Resource efficiency	2.1 Raw material extraction	Source of raw material	−C4
	2.2 Environmental effect of extraction process	Quantitative detrimental effects during the extraction	−C5
	2.3 Wastage expectancy	Probability of wastage during extraction	+C6
	2.4 Contained energy	Total amount of energy dedicated to providing the sustainable, renewable energy	+C7
3. Waste minimization	3.1 Sustainable disposal options	How favorable to create sustainable disposal options (e.g. carbon burial, incineration)	+C8
	3.2 Potential for reuse and recycling of material	Capacity for reuse and amount of total wastage during recycling	+C9
4. Environmental impact	4.1 Legislation compliance capability	Capability to comply with local and international legislation	+C10
	4.2 Pollution control	Overall ability to contribute to pollution control	+C11
	4.3 Air quality maintenance	Level of maintaining air quality using potential material	+C12
	4.4 Ozone layer influence	Level of impact to protect the ozone layer	+C13
	4.5 Toxicity	Level of generating the toxic materials (e.g. asbestos)	−C14
5. Performance capacity	5.1 Resistance to decay	Level of durability and sustainable age	+C15
	5.2 Fire resistance	Level of resistance against fire-related damage	+C16
	5.3 Thermal insulation capacity	Level of maintaining inner temperature of residential building	+C17
	5.4 Durability	Level of reliability and effective resistance again deterioration	+C18
	5.5 Buildability	Easiness of use and execution	+C19
6. Social benefit	6.1 Usage of local material	Local material usage, saving transportation cost and using local workforce	+C20
	6.2 Aesthetics	Level of visual attractiveness and comfort for use	+C21
	6.3 Health and safety concerns	Level of internal environmental and air pollution control	+C22
	6.4 Labor availability	Level of local skilled workforce	+C23

The continuity condition means that the aggregation function does not change markedly' if small changes were made to the attributes considered in the aggregation process.

$U_{x\in S}[0,1]^{x} \to [0,1]$ is a continuous aggregation function if:

$$f(x):[0,1]^{x} \to [0,1] \tag{3}$$

The monotonicity condition implies that aggregation functions are monotonic, that is, the aggregation function shows a "non-decreasing" relationship between the criteria and the aggregation maneuvers.

$$x_i' > x_i\text{, then } f(x_i') > f(x_i) \text{ where } x \in S \tag{4}$$

The idem-potencies condition is an algebraic property that belongs to the binary operation and displays the relationship if:

$$f(x, x, \cdots, x) = x \text{ where } x \in S \tag{5}$$

The associativity condition is the ability of the aggregation function to retaliate against the choice of group, which should not influence the overall result of the aggregation process.

$$f\left(f\left(x_1, x_2, \cdots\right), x_n\right) = f\left(f\left(x_1, x_2\right), \cdots, x_n\right), \quad x \in S \quad [16] \tag{6}$$

Many applications require the evaluation of a set of criteria with prioritized relationships within the set in order to reach a conclusion. [17] [18] [19].

The TOPSIS is an approach that originates from the geometric concept of displaced ideal point, which means that the criterion under investigation must be situated between the positive (most favorable) and negative (least favorable) locations [20].

Determining the weights and criteria ranking: Previous studies have discussed many methods for criteria ranking and weight determination [21] [22] [23]. There are two primary methods. The "direct choice of weights" method directly assigns weights based on the opinions and consensus of a group of experts. The "weights determination from data" method derives the weights of criteria from the data available in the same domain for aggregation purposes. We used the first method to get our weighted data set.

6. Application and Validation of Sustainability Model

Considering the complexity of the data-collection process and the research output, we conducted an empirical inquiry using a real-world, practical scenario. We collected data on roofing materials that are specifically used in residential buildings in Western Australia and are available from the two major suppliers of roofing tiles.

This validation involved the application and evaluation of two suppliers with six tile options. This hypothetical case study was based on the roofing tiles from different suppliers and different options depending on the type of material selected for the test run and the type of structure implemented. Cost was one of the factors considered; however, the most important factors were the six main criteria and related sub-criteria (see **Table 10**). The details and physical characteristics of the materials are presented in **Table 11**.

This model analyzes and ranks the sustainable options by using mathematical

Table 11. Roofing tile options.

	Roof type	Building	Structural location	Roof tile size	Roof pitch
Option 1: **two alternatives, from two different suppliers**	Timber truss pitched roof	Residential	Treated timber trussed roof with anti-con underlay, batts insulation, & concrete interlocking tiles	418 mm × 260 mm	18 - 20 degrees
Option 2: **two alternatives, from two different suppliers**	Timber truss pitched roof	Residential	Treated timber trussed roof with anti-con underlay, batts insulation, & clay terracotta tiles	418 mm × 260 mm	18 - 20 degrees
Option 3: **two alternatives, from two different suppliers**	Timber truss pitched roof	Residential	Structurally insulated roofing panels with anti-con underlay & designer ceramic tiles	418 mm × 260 mm	18 - 20 degrees

implications with the MCDM technique. The data for this pilot study were collected as part of the survey questionnaire. The experts ranked the different alternatives from the suppliers based on the criteria and sub-criteria provided to them. These values were tabulated in an MS Excel™ spreadsheet and analyzed by running the TOPSIS model. The main factors that drive the selection of roofing materials are:

1) Compliance with Australian building codes and local estate building codes.

2) House type, orientation, and building construction.

3) Local council requirements.

4) Energy management, insulation selection, and the overall anatomy of the building roof.

Roof types have different pitch values depending on building type and house style. The most common pitches for roofing in Australia are 18 - 20 degrees, depending on the materials used. The prime reason for selecting roofing material for the case study is that it can be tailored at the design stage and plays an important role in maintaining the overall sustainability ranking of building.

The three options in **Table 11** were tested against six alternatives from the two major suppliers in the Australian construction industry. The alternatives have various competitive advantages over each other.

The tabulated values in the Excel spreadsheet assigned the sub-criteria with positive or negative signs: criteria with an inverse relationship to sustainability are marked as negative and criteria that enhance the sustainability are marked as positive. The six alternatives were tested against the 23 sub-criteria related to those main six. The MCDM technique with TOPSIS gives a final ranking of these criteria and sub-criteria based on expert opinion [24].

Yoon and Hwang introduced the TOPSIS method, which proposes that the best alternative has the shortest distance to the ideal solution [25] [26]. The attribute which favors an alternative material is called the best attribute and the other is called the worst attribute. The goal of this approach is to find the Euclidean space from the ideal solution [27]. TOPSIS comprises six major steps, which are described as follows using our hypothetical problem of roofing material (roof tiles) from the two major suppliers of roof tiling.

Step 1: Calculate the normalized matrix.

The normalization is calculated using Equation (7) [28]:

$$\overline{X_{ij}} = X_{ij} \Big/ \sqrt{\sum_{j=1}^{n} X_{ij}^{2}} \quad \text{where} \quad i = 1, 2, \cdots, n \quad \text{and} \quad j = 1, 2, \cdots, m \tag{7}$$

In a matrix, the i and j belong to the first row and first column value.

Step 2: Calculate the weighted normalized matrix.

The normalized matrix is then multiplied with the weighted value as per equation (8);

$$V_{ij} = \overline{X_{ij}} \times W_j \quad \text{[27] [29]} \tag{8}$$

Step 3: Calculate the ideal best and ideal worst value.

In this step, the ideal best value is the value which suits the criteria, represented by the maximum value; the ideal best negative value which opposes the agreement of criteria is represented by the minimum value.

Step 4: Calculate the Euclidean distance from ideal best value.

This distance will be the closest value to ideal best value, using the Equation (9):

$$S^{+}{}_{\mathrm{i}} = \left[\sum_{j=1}^{n}\left(V_{ij} - V_{J^{+}}\right)^{2}\right]^{0.5} \tag{9}$$

Step 5: Calculate the Euclidean distance from ideal worst value.

This distance will be the closest value to ideal worst value, using Equation (10):

$$S^{-}{}_{\mathrm{i}} = \left[\sum_{j=1}^{n}\left(V_{ij} - V_{J^{-}}\right)^{2}\right]^{0.5} \quad [30] \tag{10}$$

Step 6: Calculate the relative closeness to the ideal solution.

The relative closeness to the ideal solution is calculated using Equation (11):

$$C_{\mathrm{i}} = S^{-}{}_{\mathrm{i}} / S_{\mathrm{i}}^{+} + S_{\mathrm{i}}^{-} \tag{11}$$

The final calculated values rank the alternatives, with 1 being the best alternative (Table 12). The MCDM can be used to solve the problem of material selection where an infinite number of alternatives exist.

Tables 13-17 show the calculations in the Excel spreadsheet. The weighted

Table 12. Ranked list of criteria.

Ranked list of criteria	
C1	Capital cost
C2	Maintenance cost
C3	Discarding cost
C4	Raw material extraction
C5	Environmental effect of extraction process
C6	Wastage expectancy
C7	Contained energy
C8	Sustainable disposal option
C9	Potential for reuse and recycling of material
C10	Legislation compliance capability
C11	Pollution control
C12	Air quality maintenance
C13	Ozone layer influence
C14	Toxicity
C15	Resistance to decay
C16	Fire resistance
C17	Thermal insulation capacity
C18	Durability
C19	Buildability
C20	Usage of local material
C21	Aesthetics
C22	Health and safety concerns
C23	Labor availability

Table 13. Data input table.

Supp lier	Name for reference	Alternatives	Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
	Data Input table			Capital cost	Maintenance cost	Discarding cost	Raw material extraction	Environmental effect of extraction process	Wastage expectancy	Contained energy	Sustainable disposal option	Potential of reuse and recycling of material	Legislation compliance capability	Pollution control	Air quality maintenance	Ozone layer influence	Toxicity	Resistance to decay	Fire resistance	Thermal insulation capacity	Durability	Buildability	Usage of local material	Aesthetics	Health and safety concerns	Labour availability
	Terracotta range	A1		7	6	6	7	6	6	4	7	7	7	7	6	4	6	3	5	4	3	5	7	6	5	4
S1	Designer ceramic range	A2		4	2	4	6	4	4	5	5	5	6	5	5	5	2	5	7	6	5	6	4	7	7	5
	Concrete range	A3		3	1	4	6	3	2	6	4	4	6	6	4	5	3	6	6	5	7	7	5	6	6	7
	Terracotta range	A4		6	6	6	7	6	5	4	7	6	7	7	6	4	6	3	4	3	4	6	6	6	6	5
S2	Designer ceramic range	A5		5	2	4	6	4	4	6	5	5	6	5	4	5	4	4	6	5	5	5	5	5	5	6
	Concrete range	A6		4	1	4	6	2	2	7	4	4	6	6	4	4	3	5	7	4	6	4	4	6	6	5
		Criteria Sign Range		−1	−1	−1	−1	−1	−1	1	1	1	1	1	1	−1	−1	1	1	1	1	1	1	1	1	1
		W (Lambda)		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 14. Normalized values table.

Normalization = N	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
A1	0.5697	0.6626	0.5145	0.4500	0.5547	0.5970	0.2998	0.5217	0.5417	0.4500	0.4719	0.4983	0.3607	0.5721	0.2739	0.3442	0.3549	0.2372	0.3656	0.5417	0.4064	0.3475	0.3015
A2	0.3255	0.2209	0.3430	0.3857	0.3698	0.3980	0.3748	0.3727	0.3869	0.3857	0.3371	0.4152	0.4508	0.1907	0.4564	0.4819	0.5324	0.3953	0.4388	0.3095	0.4741	0.4865	0.3769
A3	0.2441	0.1104	0.3430	0.3857	0.2774	0.1990	0.4497	0.2981	0.3095	0.3857	0.4045	0.3322	0.4508	0.2860	0.5477	0.4131	0.4437	0.5534	0.5119	0.3869	0.4064	0.4170	0.5276
A4	0.4883	0.6626	0.5145	0.4500	0.5547	0.4975	0.2998	0.5217	0.4643	0.4500	0.4719	0.4983	0.3607	0.5721	0.2739	0.2754	0.2662	0.3162	0.4388	0.4643	0.4064	0.4170	0.3769
A5	0.4069	0.2209	0.3430	0.3857	0.3698	0.3980	0.4497	0.3727	0.3869	0.3857	0.3371	0.3322	0.4508	0.3814	0.3651	0.4131	0.4437	0.3953	0.3656	0.3869	0.3386	0.3475	0.4523
A6	0.3255	0.1104	0.3430	0.3857	0.1849	0.1990	0.5247	0.2981	0.3095	0.3857	0.4045	0.3322	0.3607	0.2860	0.4564	0.4819	0.3549	0.4743	0.2925	0.3095	0.4064	0.4170	0.3769

Table 15. Weighted normalized values table.

Weighted Normalization = V	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
A1	0.0239	0.0172	0.0206	0.0247	0.0200	0.0197	0.0138	0.0240	0.0244	0.0247	0.0245	0.0209	0.0141	0.0200	0.0104	0.0172	0.0138	0.0102	0.0176	0.0244	0.0211	0.0174	0.0139
A2	0.0137	0.0057	0.0137	0.0212	0.0133	0.0131	0.0172	0.0171	0.0174	0.0212	0.0175	0.0174	0.0176	0.0067	0.0173	0.0241	0.0208	0.0170	0.0211	0.0139	0.0247	0.0243	0.0173
A3	0.0103	0.0029	0.0137	0.0212	0.0100	0.0066	0.0207	0.0137	0.0139	0.0212	0.0210	0.0140	0.0176	0.0100	0.0208	0.0207	0.0173	0.0238	0.0246	0.0174	0.0211	0.0209	0.0243
A4	0.0205	0.0172	0.0206	0.0247	0.0200	0.0164	0.0138	0.0240	0.0209	0.0247	0.0245	0.0209	0.0141	0.0200	0.0104	0.0138	0.0104	0.0136	0.0211	0.0209	0.0211	0.0209	0.0173
A5	0.0171	0.0057	0.0137	0.0212	0.0133	0.0131	0.0207	0.0171	0.0174	0.0212	0.0175	0.0140	0.0176	0.0133	0.0139	0.0207	0.0173	0.0170	0.0176	0.0174	0.0176	0.0174	0.0208
A6	0.0137	0.0029	0.0137	0.0212	0.0067	0.0066	0.0241	0.0137	0.0139	0.0212	0.0210	0.0140	0.0141	0.0100	0.0173	0.0241	0.0138	0.0204	0.0140	0.0139	0.0211	0.0209	0.0173

Table 16. Ideal best and ideal worst values table.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23
V+	0.0239	0.0172	0.0206	0.0247	0.0200	0.0197	0.0241	0.0240	0.0244	0.0247	0.0245	0.0209	0.0176	0.0200	0.0208	0.0241	0.0208	0.0238	0.0246	0.0244	0.0247	0.0243	0.0243
V−	0.0103	0.0029	0.0137	0.0212	0.0067	0.0066	0.0138	0.0137	0.0139	0.0212	0.0175	0.0140	0.0141	0.0067	0.0104	0.0138	0.0104	0.0102	0.0140	0.0139	0.0176	0.0174	0.0139

Table 17. Relative closeness and final ranking table.

Si+	Si−	Ci	Rank
0.0269	0.0372	0.5801	**1**
0.0325	0.0252	0.4372	**3**
0.0364	0.0272	0.4272	**4**
0.0260	0.0343	0.5686	**2**
0.0310	0.0215	0.4095	**5**
0.0399	0.0209	0.3440	**6**

values are used to give the best and worst alternatives for each criterion.

The values in Table 15, were calculated using the *formula* 8, the weights were determined using the data ranking and weights awarded by the experts according to their practical experience.

7. Conclusion

The results obtained agree with the TOPSIS ranking technique. Alternative 1 is ranked at first position: this is the best alternative available if we consider all of the 23 criteria weighted by the experts. The remaining alternatives are ranked accordingly considering the rest of criteria the best suitable for those materials.

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Conflicts of Interest

The authors declare no conflicts of interest.

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