A Customizable, Multi-stage Multi-criteria Decision Analysis Approach for Material-Supplier Selection Problem in SMEs: A Case Study of Insulated Housing Products

by

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Abstract

This research develops a multi-stage multiple criteria decision making (MCDM) approach for combined supplier-selection, material selection problems. The method has been exemplified through an industrial case study on the development of insulated skirting products. Namely, a Canadian distribution company has been long supplying the Canadian market with skirting products for manufactured homes, but recently has had issues with their overseas material supplier, particularly due to increased exchange rates. Hence, it has desired to shift their supply stream to a local manufacturer. There exist a large number of potential manufacturers that would be suitable for this new partnership. It has been crucial to scrutinize the decision alternatives systematically in order to rank and allow for the optimal selection of the supplier(s) and their skirting products.

When manufacturing suppliers are changed for a business, a natural consequence is that the end product’s material properties would also change, hence the need for a rigorous material testing as part of a multiple criteria decision making process. A step-by-step procedure has been developed here that combines supplier and material selection sub-decisions in order to find the most suitable alternative, using a hybrid of multiple criteria optimization techniques. The procedure accounts for the required decision accuracy and time-sensitivity measures that a production manager would face under different decision scenarios. The case study shows that if the company’s business situation is time-critical and the decision accuracy may not be of primary concern, a simple non-compensatory MCDM method would suffice. Otherwise, more structured compensatory methods should be employed. The criteria proposed for the case study have been selected based on the company staff feedback. The presented methodology is customizable and may be applied to other similar supplier decision making problems. Correlation analysis has also
performed to ensure the independence of the quantitative material criteria, as required per assumptions of the standard MCDM methods.
Lay Summary

Supplier selection for companies usually occurs when a new product must be made or an older supplier has to be changed for various reasons, including budgetary considerations. As suppliers change, however, the materials that are provided also often change. It is important to consider the qualities of the suppliers as well as the materials they carry concurrently. This MASc research presents a methodology for the screening and selection of an optimal supplier by combining supplier and material selection contexts, using a hybrid of multiple criteria decision making (MCDM) techniques. The methodology is scenario dependent, as it uses different mathematical techniques of varying complexity depending on the decision situation surrounding the given industrial application. It further uses a real-world case study to demonstrate the application of the method.
Preface

This research is based on an industrial project supported by an anonymous Canadian company, and awarded by the Mathematics of Information Technology and Complex Systems (MITACS) research organization.
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<th>Description</th>
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<td>MCDM</td>
<td>Multiple Criteria Decision Making</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl Chloride</td>
</tr>
<tr>
<td>DM</td>
<td>Decision Maker(s)</td>
</tr>
<tr>
<td>MADM</td>
<td>Multiple Attribute Decision Making</td>
</tr>
<tr>
<td>MODM</td>
<td>Multiple Objective Decision Making</td>
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<tr>
<td>EBA</td>
<td>Elimination by Aspects</td>
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<tr>
<td>SAW</td>
<td>Simple Additive Weighting</td>
</tr>
<tr>
<td>AHP</td>
<td>Analytic Hierarchy Process</td>
</tr>
<tr>
<td>TOPSIS</td>
<td>Technique for Order Preference by Similarity to Ideal Solution</td>
</tr>
<tr>
<td>BWM</td>
<td>Best-Worst Method</td>
</tr>
<tr>
<td>DL</td>
<td>Digital Logic</td>
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<tr>
<td>MDL</td>
<td>Modified Digital Logic</td>
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<tr>
<td>SS</td>
<td>Supplier Selection</td>
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<tr>
<td>MS</td>
<td>Material Selection</td>
</tr>
<tr>
<td>MA</td>
<td>Material Availability</td>
</tr>
<tr>
<td>TC</td>
<td>Technological Capability</td>
</tr>
<tr>
<td>YIB</td>
<td>Years in Business</td>
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<tr>
<td>MFE</td>
<td>Mean Failure Energy</td>
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Finally, I would like to thank my family for their support and love, without which none of my academic successes would be possible.
Dedication

To my

Family

&

Best friends

Without whom none of this would have been possible.
Chapter 1: Introduction

1.1 Background

Before a new product is manufactured, it needs to undergo some form of design process. Product design is often defined by means of four steps [1]:

- Idea development: The need is recognized and preliminary design concepts are established.
- Concepts screening: Different design concepts are evaluated against the product objectives, followed by screening the concepts.
- Preliminary design and testing: The selected preliminary design is created and it undergoes prototyping and market testing.
- Final design: The design of product is fine-tuned and finalized for formal launch.

The relevance of this study is to the final design stage, where one of the main tasks of manufacturers/designers is “identifying specific materials needed for the product and the suppliers that can be used” during business [1].

Supplier selection is one of the most important issues for manufacturing industries [2]. Criteria that are considered in such selection problems may be qualitative or quantitative [3]. The selection also often requires different combinations of mathematical decision models (e.g. compensatory and noncompensatory [2]), in order to meet diverse sub-criteria of a supplier selection problem. For instance, when considering different suppliers for a given company’s product, ultimately the materials used for the product also change. Each material has its own set of mechanical and physical properties that will determine how it performs in service;
additionally, it may have different aesthetics that will determine how the users would perceive the new product [4]. Accordingly, for the success of a new production plan, it is vital that companies select their suppliers based on general business capabilities of the supplier candidates, combined with their engineering technical capabilities (such as quality and properties of the materials and manufacturing processes applied) [5]. Systematic multiple criteria decision making (MCDM) methods can be developed and employed for such multi-faceted supplier selection problems, as exemplified in the current thesis.

This thesis was inspired by an industrial project (case study) performed at a local small to medium enterprise (SME). The company is located in Kelowna, BC, and currently distributes insulated house skirting products to the Canadian market, using US-based manufacturing suppliers. However, they have been facing increasing exchange costs recently and have opted to shift to a local supplier. Nationally, there are a large number of options (alternatives) that can be considered as new potential suppliers. It is critical to develop a systematic way to differentiate between the numerous alternatives in order to select the overall, most optimum supplier, while ensuring the material properties and performance of the end product are maintained, or even improved.

1.2 Objectives and Scope

The general scope of this research, through a SME-based case study, is to use multiple criteria decision making (MCDM) techniques to aid in selecting the best suppliers for manufacturing a house skirting product in Canada. The targeted methodology is “customizable” for different
scenarios surrounding similar decision making problems. For example, in our case study, the company has been looking to change its material supplier from the U.S. to Canada and has a certain number of criteria determined by the client with regards to both supplier and material selections. However, another client may use other criteria depending on their business scenarios or preferences.

The decision making method will have two steps. First, we will conduct the “Company Selection” process to find the best potential supplier(s) based on a number of business performance criteria. The candidate suppliers will be ranked and the top ranked companies will be requested to send material samples. Then, using the received samples, the second step, i.e. “Material Selection”, will be conducted, consisting of evaluating the quality of the samples by conducting various mechanical and physical tests.

The specific objectives of the thesis are:

- Develop a multi-stage decision making framework using a hybrid of different multiple criteria optimization techniques to aid decision makers in supplier selection problems;
- Demonstrate the application of the method in the development of house skirting products, through an industrial case study.

The constraints associated with the case study are the following:

- Basic design (geometry) of the product is given.
- The material for the product is PVC, but different grades can be considered.
- Suppliers based in Canada is considered only.
- The manufacturing of the product is conducted by the candidate suppliers using the extrusion process.
Specific decision making criteria are to be selected based on the direct requirements from industrial partner, complemented with the current literature.

1.3 Thesis Organization

This thesis has been arranged into five chapters, per Figure 1.1. Chapter 2 briefly reviews the theory of MCDM, and its applications in Supplier Selection as well as Material Selection problems. Chapter 3 discusses the methodology that has been developed in this thesis, and the justification behind it. The methodology will include a step-by-step procedure to perform first the supplier selection MCDM problem and then implement the material selection MCDM problem, using a hybrid of compensatory and non-compensatory techniques for comparison purposes. Chapter 4 consists of the case study (on production of insulated house skirting products) to showcase the use of the methodology with an industrial example, along with the experimental results. Chapter 5 summarizes the research findings and proposes recommendations for future work.

Figure 1-1 Organization of the thesis
Chapter 2: Literature Review

2.1 Multiple Criteria Decision Making

Throughout life, every individual is involved in ‘multicriteria’ decision making in one form or another. Sometimes these decisions are small and at times very important. From the beginning of conscious thought up to old age, humans are making decisions. Decision making involves choosing a potential option from a set of existing or potential new alternatives [6]–[8]. Decision making problems can range e.g. from choosing which job to take, to selecting the best vehicle that fits one's needs; the problems that decision makers (DM) have to consider usually involve multiple conflicting criteria in nature [9], [10]. The decision making process is formally known as ‘multiple criteria decision making’ or MCDM [11].

The highly diverse MCDM problems in real-world can be divided into two branches; Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM) [9]. MODM does not involve problems that have ‘predetermined’ alternatives [6], [12]. It involves problems with a continuous decision space [13], [14]. It is more appropriate for design problems rather than selection [6]. MADM involves problems with decision spaces that are discrete and the related techniques revolve around selecting a number of options from alternatives that are usually finite and predetermined [13]–[15]. All categories of MADM problems have some common features/definitions as follows [9]:

- Alternatives: a limited set of potential solutions are screened, ranked and selected.
Multiple attributes/criteria: The problem at hand consists of a number of attributes. Appropriate attributes must be selected by the DM and the number of selected attributes depends on requirements and constraints associated with the problem.

Incommensurable units: Every attribute consists of a distinct measurement unit. These can be expressed numerically or even in nonnumeric terms.

Attribute weights: Information about the importance of attributes relative to one another is required in most MADM methods.

Decision Matrix: MADM problems can be presented in a matrix form, where normally rows represent alternatives and columns represent the attributes.

A taxonomy of MADM methods was developed by Yoon and Hwang [9] as seen in Figure 2.1. They are classified depending on the type of information available to the decision maker. For instance, if there is no available information on relative priority of criteria, then the Dominance method would be suitable to use. If information regarding the decision environment is optimistic or pessimistic in nature, then Maximax or Maximin method would be suitable, respectively.

If there is some availability in the information of the relative priority of attributes, other methods can be employed. For example, if such information is provided as standard levels in a given decision making problem (e.g. maximum available production budget, or minimum level of required mechanical properties from design perspective, etc) then Conjunctive and Disjunctive methods would be suitable. Elimination by Aspect (EBA) or Lexicographic method may be employed if the information provided assesses the attributes weights by an ordinal scale. Otherwise, when the DM assesses the weights by cardinal scales, methods such as Simple
Additive Weighting (SAW), Weight Product and TOPSIS, Median Ranking Method and Analytic Hierarchy Process (AHP) etc. may be used.

According to Hwang [16], MADM methods can also be classified by given data type. He identified data as rank, Yes-No, and numeric types. In problems which involve rank data, Dominance and Lexicographic methods would be applied. In problems with Yes-No data type,
Dominance, Lexicographic and EBA would be suitable. Problems involving numeric data types would benefit from SAW, TOPSIS, etc.

From another practical viewpoint, MADM methods can be divided into two main groups of ‘compensatory’ and ‘non-compensatory’ [15]. Non-compensatory techniques allow for no trade-offs between the attributes in a given problem. Low scores in one attribute cannot be offset by better scores in others. [15]. Each criteria will have equal importance in the decision making. Non-compensatory methods have the advantage of being fairly simplistic and are ideal for a DM having insufficient ability and knowledge. [15]. Examples include the dominance, elimination by aspects, lexicographic, maximax, maximin, conjunctive and disjunctive methods.[9], [15]. In contrast, compensatory methods do allow for trade-offs between attributes [15]. An alternative with slightly low scores in some criteria may turn out to be the best solution if it performs well in the other criteria. Examples of such methods are SAW, weighted product and TOPSIS. Overall, compensatory methods tend to be more cognitively demanding [9].

More details of select MADM methods as pertinent to this research are discussed in the following section.

2.2 Considerations of Select MCDM Techniques

2.2.1 Dominance

An alternative A1 is more preferable than an alternative A2 and would be selected if it performs better than A2 on one or more criteria, while simultaneously not being worse on any other criteria [17]. A nondominated alternative is one that is not exceeded in every criteria that is being considered by another alternative [9].
2.2.2 Maximin

In an occasion where there is no information regarding which criteria dominates the outcome, a pessimistic view should be taken [9]. The alternative of which the worst criteria score is better than the worst score of the other alternatives should be selected [9]. The logic is that the DM should not select an alternative that has the least attractive criteria [17].

A DM will assess the values of criteria for the alternatives and identify the one with the lowest value, then will choose the alternative with the highest among them [15]. Here, the alternative is represented by its weakest criteria and all other attributes are disregarded [15]. Since in many cases the smallest value is from different criteria, this method requires the criteria to be measured (quantified) on the same scale, so that their values can be comparable [15].

If A⁺ is the preferred alternative, it should satisfy equation 2.1 [15].

\[ A^+ = \{ A_i | max_i min_j r_{ij} \}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n \]  
(2.1)

Where \( r_{ij} \) is a comparable (normalized) scale of \( x_{ij} \) (original value of alternative \( i \) under criteria \( j \)).

2.2.3 Maximax

Maximax makes selection based on the highest criteria value [15]. The highest criteria values of each alternative are identified [15] and the alternative with the largest of these values would be selected. The logic is that the “best of the best” should be chosen. An alternative is represented by its strongest criteria and all other attributes are disregarded [15]. Different type of attributes may be compared in this selection method, and hence they should use the same scale for comparison [15].

If A⁺ is the preferred alternative under this method, it should satisfy equation 2.2 [15].
\[ A^+ = \{ A_i \mid \max_i \max_j r_{ij} \}, \ i = 1, 2, \ldots, m; \ j = 1, 2, \ldots, n \] (2.2)

Where \( r_{ij} \) is a comparable (normalized) scale of \( x_{ij} \).

### 2.2.4 Elimination By Aspects

Elimination by Aspects (EBA) was developed by Tversky [18]. He described EBA as being similar to the Lexicographic method where one criterion is considered at a time. However, there are some differences between the two. Firstly, the criteria are not ordered on their importance before the rejection process, but on their probabilistic discrimination power [9], [18]. Also, alternatives are rejected when they do not satisfy a threshold or standard. This process goes on until only one alternative is left [18].

For instance, if the most and second most effective aspect (criteria) to use to reject alternatives are denoted as \( X_1 \) and \( X_2 \) respectively, then the preferred alternative set \( A^1 \) is represented by equation 2.3 [9].

\[ A^1 = \{ A_i \mid \text{satisfies } X_1 \}, \quad i = 1, 2, \ldots, m \] (2.3)

If the \( \{ A^1 \} \) set only contains one element, then this alternative will be selected. Otherwise, one can consider next best set (equation 2.4).

\[ A^2 = \{ A^1 \mid \text{satisfies } X_2 \}, \quad i \in \{ A^1 \} \] (2.4)

If only one element is in the \( \{ A^2 \} \) set, then that would be the alternative that is preferred. If not, then this is continued with \( X_3 \) and so on until a single alternative is found.
2.2.5 Conjunctive Method

In this method, a minimum threshold is set for each of the criteria and an alternative must possess value above these thresholds in order to be selected [9], [19]. Rejection can be caused by failure of even one attribute under the minimum value set [9]. An alternative would be suitable under this method if it satisfies equation 2.5 [9]:

\[ x_{ij} \geq x^0_j, \quad j = 1, 2, \ldots, n \] (2.5)

Where \( x^0_j \) is the smallest value that is acceptable for the \( j \)th criterion.

The values selected for the thresholds are an important component in rejecting unsuitable alternatives. If these values are set too high (too conservative), then all the alternatives may be rejected. However, setting them too low would have an opposite effect and all or too many alternatives may be left. One possible way to cope with this problem would be to raise the thresholds in an iterative manner, in order to narrow down the alternatives until one is remaining. [9]

2.2.6 Disjunctive Method

The disjunctive method also sets a minimum threshold for each criterion, and alternatives are essentially evaluated on their best criteria values [9], [19]. Selection of an alternative will occur if it satisfies the minimum threshold of at least one (most important) criterion. An alternative would be suitable under this method if it satisfies equation 2.6 [9]:

\[ x_{ij} \geq x^0_j, \quad j = 1 \text{ or } 2 \ldots \text{ or } n \] (2.6)

Where \( x^0_j \) is the smallest value that is acceptable for the \( j \)th criteria.
This method would make sense to use if an alternative is being sought for acceptable performance at least under one criterion [19]. When the threshold of only a single criterion is required to be exceeded, a majority of alternatives will not be rejected. Hence, the values may need to be set near or at the highest level. In the scenario that all the alternatives are rejected, the threshold can be lowered for one or more criteria and the process is restarted until the ideal alternative is found [9].

2.2.7 Lexicographic Method

Fishburn [21] described sequential screening procedures as an example of where the lexicographic concept can be used. Alternatives are initially screened with regards to a criterion and then the alternatives that are not rejected are screened again under another (next important) criterion. This process may continue until the remaining alternatives in the last step are ranked.

Yoon and Hwang [9] described the lexicographic method as appropriate for decision making scenarios where the consideration of one attribute outweighs all others. This includes scenarios where “buy cheapest” is the rule. In such situations, alternatives are screened under the most important criterion first. The best one is selected and the process ends. If there is a tie between two or more alternatives, then these alternatives are compared under the next important criterion over and over again until the best one is selected or comparisons have been made under all of the criteria. If more than one alternative is left in the end, then they are regarded as equal. If the most and second-most important criteria are denoted as $x_1$ and $x_2$, respectively, then the preferred alternative set $A^1$ is represented by equation 2.7.

$$A^1 = \{A_i \mid \max_i x_{i1}\}, \quad i = 1, 2, ..., m$$  \hspace{1cm} (2.7)
If $A^1$ has only one element then this alternative will be selected. Otherwise, we will consider $A^2$, represented by equation 2.8:

$$A^2 = \{ A^1 \mid \max_i x_{i2} \}, \quad i \in \{ A^1 \}$$

(2.8)

Again, if only one element is in $A^2$, then that would be the alternative that is preferred. If not, then this is continued until a single alternative is found or all criteria have been used for comparison.

### 2.2.8 Simple Additive Weighting

This is one of the most popular MCDM methods to date. In this method, contributions of every criteria are added in order to get a score for each alternative [9]. In order to use this technique, the various criteria, usually having different units need to be comparable along a scale; and hence some form of data normalization is required (usually linear normalization). Each alternative is scored by multiplying and adding the normalized values of the criteria by criteria weights; the latter may be assigned directly by the DM or determined using some other weighting methods, which will be discussed in other sections of the thesis. This scoring method is represented by equation 2.9 [9]:

$$V_i = \sum_{j=1}^{n} w_j r_{ij}, \quad i = 1, \ldots, m$$

(2.9)

Where $V_i$ and $r_{ij}$ are the value (score) of alternative $A_i$ and the normalized value of $x_{ij}$, respectively. And, $w_j$ is the weight of criteria $x_j$. 
2.2.9 Weighted Product Method

This method is quite similar to SAW but different in that when calculating the value of alternative $A_i$, instead of summation, multiplication is used [13]. Also, it does not require normalization of dimensions to a comparable scale and is sometimes referred to as “dimensionless analysis” [13]. Furthermore, the weights are used as exponents of the criteria values [9]. This scoring method is represented by equation 2.10 [9], [13]:

$$V_i = \prod_{j=1}^{n} x_{ij}^{w_j}, \quad i = 1, \ldots, m$$  \hspace{1cm} (2.10)

Where $V_i$ is the value of alternative $A_i$ and, $w_j$ is the weight of criteria $x_j$.

2.2.10 TOPSIS

A Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was developed by Hwang and Yoon [15]. The idea is that the best alternative should have the shortest and longest distances from the positive-ideal (best imaginary) and negative-ideal (worst imaginary) solutions, respectively. The steps required to find the preferred alternative are as follows [15]:

Step 1: The normalized values are calculated by using vector normalization for $r_{ij}$ (equation 2.11):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \quad i = 1, \ldots, m; j = 1, \ldots, n.$$  \hspace{1cm} (2.11)

Step 2: The weighted normalized values are calculated for $v_{ij}$ (equation 2.12):

$$v_{ij} = w_j r_{ij}, \quad i = 1, \ldots, m; j = 1, \ldots, n.$$  \hspace{1cm} (2.12)

Step 3: Determine the positive-ideal ($A^*$) and negative-ideal ($A^-$) solutions.

$$A^* = \{v_1^*, v_2^*, \ldots, v_j^*, \ldots, v_n^*\} = \{(\max_i v_{ij} | j \in J), (\min_i v_{ij} | j \in J') | i = 1, \ldots, m\}$$  \hspace{1cm} (2.13)
\[ A^- = \{v_1^-, v_2^-, \ldots, v_j^-, \ldots, v_n^-\} = \{(\min_i v_{ij} | j \in J), (\max_i v_{ij} | j \in J') | i = 1, \ldots, m\} \]  

(2.14)

where \( J \) and \( J' \) are sets of benefit- and cost-type criteria, respectively.

Step 4: Determine the separation (distance) measures from the positive-ideal and negative-ideal solutions.

\[ S_i^* = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^*)^2}, \quad i = 1, \ldots, m. \]  

(2.15)

\[ S_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2}, \quad i = 1, \ldots, m. \]  

(2.16)

Step 5: Determine relative closeness to the positive-ideal solution (equation 2.17):

\[ C_i^* = \frac{S_i^-}{S_i^* + S_i^-}, \quad i = 1, \ldots, m, \quad 0 \leq C_i^* \leq 1 \]  

(2.17)

Alternatives with higher \( C_i^* \) are preferred.

### 2.2.11 Median Ranking Method

When qualitative data is available, we can obtain rank data and employ them for MADM using the median ranking method. The ranks of criteria often conflict with one another, but it is important for the DM to get a consensus from the ranks [9]. A distance function was developed by Cook and Seiford [22] in order to determine consensus ranking. It acts as a measure of agreement or disagreement between ranks [22]. When assuming equal importance between attributes, then for \( A_i \) to be the \( k \)th rank overall, the rank distance is defined as equation 2.18.

\[ d_{ik} = \sum_{j=1}^{n}|s_{ij} - k| \]  

(2.18)

Where \( s_{ij} \) is the attribute-wise rank of \( A_i \).

If the different criteria have different relative importance, the distance equation becomes [9]:

\[ d_{ik} = \sum_{j=1}^{n}w_j|s_{ij} - k| \]  

(2.19)
Where \( w_j \) is the weight of the criteria. Then, for the alternatives to have final ranks assigned to them, the Hungarian Method [23] can be used.

### 2.2.12 Best-Worst Method

The Best-Worst Method (BWM) was recently developed by Rezaei [24], [25] and is a vector based MCDM technique as opposed to matrix based methods. From the attributes, the DM selects the most important one, or the “best”, and the least important one, or the “worst”. The attribute that is the “best” is then compared with each of the other attributes. Similarly, then the “worst” attribute is compared with each of the other attributes, and finally the criterial weighting are found. The method consists of the following detailed steps:

**Step 1:** The set of decision criteria \( \{c_1, c_2, \ldots, c_n\} \) needed for the decision making should be determined by the DM.

**Step 2:** Determine the best and worst criteria based on the DM experience.

**Step 3:** Determine the preference of the best criterion over all the other criteria by using a number between 1 and 9; where 1 indicates equal preference and 9 indicates extreme preference. The best-to-others resulting from this will be \( A_B = (a_{B1}, a_{B2}, \ldots a_{Bn}) \), where \( a_{Bj} \) shows the preference of the best criterion \( B \) over criterion \( j \), with \( a_{BB} = 1 \).

**Step 4:** Determine the preference of all the other criteria over the worst criterion by using a number between 1 and 9. The others- to-worst resulting from this will be \( A_W = (a_{1W}, a_{2W}, \ldots a_{nW})^T \), where e.g. \( a_{1W} \) shows the preference of the criterion 1 over worst criterion \( W \); note that \( a_{WW} = 1 \).

**Step 5:** Determine the optimal weights of criteria \( (w^*_1, w^*_2, \ldots, w^*_n) \). The optimal weighting for the attributes is one where \( w_B/w_j = a_{Bj} \) and \( w_j/w_W = a_{jW} \). To meet these conditions the maximum
absolute difference of the set \( \{|w_B - a_{Bj}w_j|, |w_j - a_{jw}w_w|\} \) should be minimized and the problem can be formulated as follows [24]:

\[
\min \max_j \{ |w_B - a_{Bj}w_j|, |w_j - a_{jw}w_w| \}
\]  

(2.20)

Such that:

\[
\sum_j w_j = 1, w_j \geq 0, \text{for all } j
\]

This optimization problem can be transferred to a linear programming as follows:

\[
|w_B - a_{Bj}w_j| \leq \xi_L, \text{for all } j
\]

\[
|w_j - a_{jw}w_w| \leq \xi_L, \text{for all } j
\]

\[
\sum_j w_j = 1
\]

\[
w_j \geq 0, \text{for all } j
\]

This linear problem gives a unique solution, where the optimal weights \((w_1^*, w_2^*, \ldots, w_n^*)\) and \(\xi_L\). \(\xi_L\) can be considered an indicator of consistency; the closer its value is to zero, the higher will be the consistency.

2.2.13 AHP

Saaty [26] developed the Analytical Hierarchical Process (AHP). The method decomposes decision making problems into a hierarchical form [13]. This hierarchy consists of at least three levels: the goal at the first, the criteria at the second, and the competing alternatives on the third level.
Pair-wise comparisons are utilized to assess the inputs from the decision makers or experts. Then, these are used in order to determine the relative importance (weights) of the criteria [27]. Similarly, pair-wise evaluation of alternatives is performed with regards to how well they satisfy each criterion [27]. Then the performance score of each criterion is multiplied by its weight and summed over all criteria to obtain the overall performance score for all alternatives [27].

2.2.14 Modified Digital Logic

The Digital Logic (DL) method is a simple yet very effective technique to generate weights, especially for DMs with less experience. Pairwise comparisons of attributes is conducted and a score of 1 is assigned to the attribute that is more attractive, and 0 to the attribute that is less attractive. A modified version of this called the Modified Digital Logic (MDL) was developed by Dehghan-Menshadi et al. [28]. It is based on the same idea of the DL method but instead of just binary scores of 1 and 0, it uses other scores (1, 2 or 3). Attributes that are less attractive are assigned a score of 1 and 3 is assigned to attributes that are more attractive. Attributes that are equally attractive can both receive a score of 2. Eventually, these ranking scores are summed and normalized to final the weighting factors [27].

2.3 Supplier Selection as an MCDM Problem

Choosing the right suppliers is a critical element for businesses looking to bring down costs, increase competitiveness and improve customer satisfaction [29]–[40]. Quality of products and services is also associated with proper supplier selections [36], [41].
Additionally, materials and services that are purchased through the suppliers account for a significant amount of the overall product costs, up to 80% in some industries [39], [42]. With so much dependent on effective suppliers, the selection of poorly performing suppliers can have serious consequences that can risk the success of a business [38], [41], [43].

Supplier selection (SS) requires assessing candidate suppliers on their capabilities with the goal of providing a continuous flow of service and material to support the business activities [31], [41]. This includes collecting data and then analyzing the selection aspects that may influence the final success of the business [33]. Generally speaking, the best suppliers are the ones which supply products or services that are able to match or go beyond the requirements of the business [37].

The selection of the best suppliers is dependent on a number of alternatives and usually conflicting criteria, making supplier selection an MCDM problem [44], [45]. These criteria may be qualitative and quantitative in nature, such as quality and price [36], [37], [39], [45]–[49]. A preferred supplier may be associated with the lowest cost, but also supplier’s products with lower quality, or e.g. poor timely delivery performance may be of concern [31]. Traditionally, suppliers were selected based on cost alone, but now consideration of other criteria is taking place and the decision process is moving towards a trend of searching for fewer, more trustworthy, and more collaborative partners that can form longer-term relationships [32], [39], [43], [46], [50], [51]. Focusing on cost criteria alone can lead to a business purchasing the cheapest alternative and leave them with a product that is not necessarily capable of functioning as originally designed, hence causing great potential hits to business competitiveness [51].
The current trend in research in this field is to create mathematical models using decision making techniques [52]. They usually involve some form of pre-qualification that takes place from the pool of potential suppliers, before the selection of the best supplier from the ones that pass the minimum business performance requirements [43], [53]. When businesses want to select a supplier selection method, their specific needs must be accounted for, therefore there is need for a certain level of flexibility with testing a sufficient number of different selection methods (here MADM methods) depending on various applications or scenarios [35].

There are numerous case studies that have used MCDM for the supplier selection problem. Hruška et al. [54] proposed a model using AHP and applied it to an example that selects the best supplier among three potential candidates. Wang [55] developed a model using AHP for the supplier selection of maintenance and repair parts. Kamath [56] proposed a methodology using AHP to assess raw material suppliers for a steel pipe manufacturing plant. Tahriri et al. [57] used AHP and developed a supplier selection model for a steel manufacturing company. Hemaida and Schmits [58] developed a model using AHP for the selection of the optimal supplier to subcontract for a paint-dipping tank. Haridasan and Sudharsan [59] used AHP to develop a rating system for supplier selection of pipes for the engineering construction industry. John et al. [60] worked on a study using AHP to assess suppliers for valves. Tam and Tummala [61] created a model using AHP for selection of a telecommunication system supplier. Hudymáčová et al. [62] developed a methodology using AHP for supplier selection of grub screw parts. A fuzzy version of AHP has also been used in the literature. Kahraman et al. [63] used a fuzzy AHP model for supplier selection of aspirators for a white goods manufacturer. Chan et al. [64] created a method
for the selection of a global supplier by implementing fuzzy AHP. Kilincci and Onal [65] used fuzzy AHP to develop a process of supplier selection for a washing machine production company.

Other techniques used in the literature to evaluate suppliers include e.g. the fuzzy TOPSIS method. Sevkli et al. [66] proposed a fuzzy TOPSIS model to select forging parts for propellor shafts. Kumar et al. [67] illustrated a model using fuzzy TOPSIS for a steel manufacturing plant that is seeking raw materials. Gupta and Barua [68] created a study using fuzzy TOPSIS to select suppliers for an automobile company. Nag and Helal [69] used fuzzy TOPSIS to select a supplier for a pharmaceutical distributor.

Hsu and Hu [70] used ANP (analytic network process) to incorporate hazardous substance management to the supplier selection problem. Tan et al. [71] developed a model using ANP and applied it for the supplier selection of a diesel engine manufacturing firm. Alidrisi [72] showed a model for the supplier selection problem for electric companies using ANP. Gencer and Gurpinar [73] used ANP to select a supplier for an electronic company. Xiang, Feng and Yong [74] proposed a method based on ANP for the supplier selection of building engineering materials. Vinodh et al. [75] developed a model using fuzzy ANP for the selection of a supplier for an electronic switch manufacturing company. Dargi et al. [76] developed a framework to support the selection of a supplier in the automotive industry. Pang [77] proposed a methodology using fuzzy ANP to select the best supplier for a technology manufacturing firm purchasing key components for a new product. Kang, Lee and Yang [78] proposed a model using fuzzy ANP to for the selection of packaging company for the semiconductor industry. Wei et al. [79] proposed...
a model using fuzzy ANP to help the managers generate weights for the supplier selection problem.

Abdel-Baset et al. [80] developed a model using VIKOR for the supplier selection for an importing company. Cheraghalipour et al. [81] considered a framework using VIKOR to select a supplier for an agricultural industry corporation. Sanayei, Mousavi and Yazdankhah [82] proposed a fuzzy VIKOR method to select a supplier for new components of a new product in the automobile part manufacturing industry. Dai, Liu and Zhang [83] proposed a methodology using fuzzy VIKOR for supplier selection of the optimal logistic service provider.

Birgun and Cihan [84] developed a model using ELECTRE and illustrated for a computer hardware manufacturing firm searching for a supplier of their new part. Kumar et al. [85] developed a method using ELECTRE and demonstrated the supplier selection for spherical roller bearing. Cristea and Cristea [86] proposed a methodology using ELECTRE to select the optimal supplier for the flexible packaging industry. Sevkli [87] proposed using fuzzy ELECTRE to select supplier of forging parts for propeller shafts. Hanane, Brahim and Bouchra [88] proposed a methodology using PROMETHEE to select suppliers of process chemicals used for refining processes. Chang et al. [89] proposed a method that uses fuzzy DEMATEL to develop supplier selection criteria. Nouranifar and Montazer [90] suggested using fuzzy COPRAS for the selection of optimal raw materials supplier. The summary of the above case study applications can be found in Table 2.1.
<table>
<thead>
<tr>
<th>MCDM</th>
<th>Study</th>
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</tr>
</thead>
<tbody>
<tr>
<td>AHP</td>
<td>A model is proposed with an application of a manufacturing company selecting optimal selection from three potential suppliers.</td>
<td>[54]</td>
</tr>
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<td>A model is developed to select a supplier for maintenance and repair parts.</td>
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</tr>
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<td>AHP</td>
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<tr>
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<td>[61]</td>
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</tr>
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</tr>
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<td>[64]</td>
</tr>
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<td>A process is developed for the supplier selection for a washing machine production company.</td>
<td>[65]</td>
</tr>
<tr>
<td>Fuzzy TOPSIS</td>
<td>A model for supplier selection is proposed for selection of forging parts for propeller shafts.</td>
<td>[66]</td>
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<td>A study on selection suppliers on the basis of green innovation ability for an automobile company.</td>
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<tr>
<td>ANP</td>
<td>An approach is presented that incorporates hazardous substance management into supplier selection.</td>
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<td>Fuzzy DEMATEL</td>
<td>A method is proposed for the development of supplier selection criteria</td>
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</tr>
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<td>Fuzzy COPRAS</td>
<td>A model is proposed for the selection of the optimal supplier of raw materials for a firm.</td>
<td>[90]</td>
</tr>
</tbody>
</table>

Overall, from the conducted review it appears that one of the most widely used MCDM techniques for supplier selection problems is AHP. However, it has the disadvantage of potentially suffering from rank reversals and inconsistencies due to the use of pairwise comparisons [91], [92]. Additionally, as the number of criteria and alternatives increase, it required high computational time [93]. Fuzzy AHP involves making pairwise comparisons one at a time between ‘qualitative’ factors with fuzzy data, which has been occasionally regarded as “tedious and cumbersome” [94], [95].

Similarly to AHP, rank reversals can occur in fuzzy AHP, especially when a new alternative is included [91]. Also, a disadvantage of Fuzzy AHP is that it consists of complicated fuzzy operation and lacks ways to address consistency [96]. In contrast, one of the limitations that Madi et al. [97] stated for most fuzzy TOPSIS methodologies is that they have reliability issues. A number of fuzzy MCDM hybrids have been also proposed in the literature, involving complex computation process and outcomes that may be counterintuitive [98], [99]. According to Mahmoud and Garcia [100], for a method to be most effective, understanding the method should require minimal time and effort because this will lead to better use and effective implementation.
In general, non-expert decision makers (DMs) often prefer “simple, more transparent methods”[101].

Other methods exist that can be potentially used for the supplier selection problems, such as the Median Ranking method (which is one of the main methods to be considered in this thesis). In particular, the median ranking method has been shown to be effective for qualitative decision making cases [9]. The method is inspired from an established group decision making technique [102], in the realm of consensus rankings [103]. It generates an optimum solution to the distance-minimizing type of consensus problem. Instead of combining preferences of a number of DMs form a consensus, Yoon and Hwang [9] proposed combining attribute ranks instead to form a consensus ranking, hence, giving the ability to rank the alternatives.

2.4 Material Selection as an MCDM Problem

Material selection (MS) is an important part of engineering design and its objective is to choose the most effective materials for a specific application so that the product can perform as intended by designers, according to some predetermined technical requirements [104]–[111]. The MS is critical for competitiveness and profitability of all manufacturing sectors [112], [113]. It is also a crucial aspect to ensure high performance and reliability of the products with lower costs [105], [108]. It can also drastically cause changes to the final design and impact customer satisfaction [114]. Poor selection of a product material can impact the reputation and profitability of the business [106].
Material selection typically occurs during the initial design stages, or when changing the product to fit market demands, or due to past product failure [107]. The easiest way of choosing or replacing a material is to use designers (here DMs) experience or trial and error methods; however, these can be quite time- and resource-consuming and may not lead to an optimal solution [108], [115]. Effective MS consists of determining the product’s property requirements, creating a list of alternatives and finally selecting the optimal material [104], [116].

A material selection problem may take many types of properties into account including electrical, mechanical, physical, chemical properties [111], [117]. Example of these properties would include tensile strength, density, the Young’s modulus, etc. [112], [118]. There already exist a large number of materials available on market for selection in different engineering applications and the number is increasing rapidly by innovations on new material systems (e.g. new composites), each having their own advantages and drawbacks [105], [106], [112], [119]. Hence, it is crucial that the designers have complete understanding of the properties of the materials options in a given application [105], [113]. Many products have failed in the past due to poor material selection and that did not fully map the considered properties to final requirements of the product [113]. These properties can be often determined by conducting engineering tests [120].

Material selection consists of numerous criteria and alternatives that are often conflicting in nature, where trade-offs between the properties may need to be considered; hence raising the application of MCDM methods [105], [106], [109], [121], [122]. MS also usually involves non-commensurable units which may be quantitative and qualitative [105], [112], [121], [122]. Since
selection of the right material can be a challenging and time-consuming task [105], [106], [115], [119], [121], [122]. DMs would benefit from employing some decision-aids to assist the decision making process [107], [115].

There has been extensive use of MCDM in the literature for materials selection in a variety of product designs. Chauhan et al. [123] used SAW for the selection of piezoelectric material for ultrasonic transducers and actuators. Taherian and Nasr [124] used SAW for the material selection of nanocomposite bipolar plate in fuel cells. Senyigit and Demirel [125] used SAW for the selection of packaging material for carbonated drinks. Taherian [126] used SAW for the material selection of composite and metallic bipolar plates in proton exchange membrane fuel cells. Torrez et al. [127] used SAW to obtain the material selection for light-weight naval crafts. Anupam et al. [128] uses SAW for the selection of raw materials for paper and pulp industry. Taka et al. [129] developed an optimal procedure for the material selection of the best tool insert. Mansor et al. [130] used SAW to select the most appropriate thermoplastic matrix based on design specifications. Xie [131] proposed a procedure using TOPSIS for the material selection of electrical insulation. Shanian and Savadogo [132] developed a method using TOPSIS to select material for metallic bipolar plates for polymer electrolyte fuel cell. Milani et al. [120] used TOPSIS to select material for gear systems. Govindan et al. [133] used TOPSIS for the selection of material of bricks for the construction industry. Anupam et al. [134] used TOPSIS for the raw material selection for pulp and papermaking. Jee and Kang [135] developed a procedure using TOPSIS for the selection of optimal material for a flywheel.

Shanian and Savadogo [142] used ELECTRE to select the material for mass-produced non-heat-treatable cylindrical cover material. Hassan, Rosli and Redzuan [143] used ELECTRE to select material for a badminton racket. Shanian and Savadogo [144] used ELECTRE for the material selection of bipolar plates for polymer electrolyte membrane fuel cell. Mangera et al. [145] used ELECTRE for material selection for a paediatric prosthetic knee. Kiani, Liang and Gross [146] proposed a procedure using VIKOR to aid in selecting repair material for concrete structures. Ishak, Malingam and Mansor [147] used VIKOR to select the material of natural fibers used in the composites for a car’s front hood. Chatterjee and Chakraborty [148] developed a model for material selection using COPRAS. Mahmoudkelaye et al. [149] used ANP for the material selection of an exterior building enclosure. Jiao et al. [150] developed an approach using PROMETTHEE for the material selection problem and illustrated it for the selection of material for a wing-spar of a human-powered aircraft.

The summary for the literature mentioned above can be seen in Table 2.2.
As was the case for the supplier selection MCDM, each MCDM method used for material selection problems has had benefits and drawbacks and it cannot be concluded that a single techniques is generally the best [151], [152]. The mechanics of most MCDM methods are not easy to interpret and at times not understood easily, and by untrained users can often be seen as “scientific witchcraft”[152]. It is crucial for the user to have easy interpretation in order for the selected methods to be practical tools and aid decision makers in day-to-day problems [152].

Table 2-2 Recent examples of MCDM used in material selection problems

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAW</td>
<td>Material Selection for piezoelectric material for ultrasonic transducers and actuators.</td>
<td>[123]</td>
</tr>
<tr>
<td>SAW</td>
<td>Material Selection for nanocomposite bipolar plate in proton exchange membrane fuel cells.</td>
<td>[124]</td>
</tr>
<tr>
<td>SAW</td>
<td>Material selection for carbonated soft drink packaging.</td>
<td>[125]</td>
</tr>
<tr>
<td>SAW</td>
<td>Material Selection of composite and metallic bipolar plates in proton exchange membrane fuel cells.</td>
<td>[126]</td>
</tr>
<tr>
<td>SAW</td>
<td>Material Selection for light-weight naval crafts.</td>
<td>[127]</td>
</tr>
<tr>
<td>SAW</td>
<td>Material Selection for raw material for pulp and paper.</td>
<td>[128]</td>
</tr>
<tr>
<td>SAW</td>
<td>Material selection of tool and work piece combination.</td>
<td>[129]</td>
</tr>
<tr>
<td>SAW</td>
<td>Material Selection of thermoplastic matrix.</td>
<td>[130]</td>
</tr>
<tr>
<td>TOPSIS</td>
<td>Material Selection for electrical insulation.</td>
<td>[131]</td>
</tr>
<tr>
<td>TOPSIS</td>
<td>Material Selection of metallic bipolar plates for polymer electrolyte fuel cell.</td>
<td>[132]</td>
</tr>
<tr>
<td>TOPSIS</td>
<td>Material Selection of gear material.</td>
<td>[120]</td>
</tr>
<tr>
<td>TOPSIS</td>
<td>Sustainable material selection of bricks for construction industry.</td>
<td>[133]</td>
</tr>
<tr>
<td>TOPSIS</td>
<td>Raw material selection for papermaking.</td>
<td>[134]</td>
</tr>
<tr>
<td>TOPSIS</td>
<td>Material Selection of a flywheel.</td>
<td>[135]</td>
</tr>
<tr>
<td>AHP</td>
<td>Optimal material Selection for cutting tools.</td>
<td>[136]</td>
</tr>
<tr>
<td>AHP</td>
<td>Material Selection for housing for electronic device.</td>
<td>[137]</td>
</tr>
<tr>
<td>AHP</td>
<td>Material Selection of material for building of a wall.</td>
<td>[138]</td>
</tr>
<tr>
<td>AHP</td>
<td>Material Selection for semiconductor switching devices in electric vehicles.</td>
<td>[139]</td>
</tr>
<tr>
<td>AHP</td>
<td>Material Selection in screw manufacturing for minimizing environmental impacts.</td>
<td>[140]</td>
</tr>
</tbody>
</table>
Dyer et al. [153] mentions that understandable and simple methodologies are needed in dealing with MCDM problems. SAW is perhaps the most commonly used MCDM technique [154] in material selection problems. With its clear logic, simple computation and straightforward implementation, it is highly user friendly [155]–[157] and easy to interpret [158]. Among the other MCDM methods, Mousavi-nasab and Sotoudeh-anvari [151] concluded that, aside from a few exceptions, AHP and ELECTRE are generally not appropriate for the material selection problems, mostly due to their computational expenses. Furthermore, The role of weights in TOPSIS is not always intuitive [152].

In comparison of rank reversal problem of several MCDM techniques, as reviewed by Mousavi-nasab and Sotoudeh-anvari [151], SAW has had few rank reversals and the TOPSIS has performed the worst in this regard. Kaliszewski and Podkopaie [152] describes SAW as
belonging “nowadays to the folklore of the domains of decision making and expert systems” and “hardly needs much explanation” of the decision mechanisms. In fact, they describe SAW as a “natural language” and propose using it as a metamodel to explain the mechanics of the more complex (and less intuitive) MCDM techniques. Additionally, Mousavi-nasab and Sotoudeh-anvari [151] name SAW as one of the most important MCDM techniques for the material selection problem.
Chapter 3: **Methodology**

### 3.1 Background

Selecting a new material or replacing an older one is often a difficult task for designers due to the sheer number of materials available. Different factors have to be considered such as the suitability and quality of the material and finding an effective supplier to supply it consistently and promptly.

Proper supplier selection can be a crucial task for businesses. Good suppliers allow the lowering of costs and their proper selection can affect the success of the business. They also allow for flexibility and aid in new design and development efforts. All materials have different properties and they all have different benefits and drawbacks for any given application. Properties of materials can be obtained using mechanical tests. Conducting own tests by businesses is often preferred because it ensures reliability of the results and also sometimes the grade and properties of the material is not known.

It is typical that the number of materials being considered to be fairly large at an early stage of selection. To simplify the material selection process, it is important to have the potential alternatives to undergo some form of screening using MCDM. The next step would be choosing the smaller number of the screened options for testing [159], and eventually comparing them again using MCDM.

As discussed in Chapter 2, the decision making techniques can be loosely divided into two categories: ones that are compensatory and ones that are noncompensatory. The key difference
between these two is that compensatory methods can allow trade-offs between attribute values. That is, that good values on some criteria can make up for bad values on other criteria. However, in noncompensatory techniques that is not the case. Compensatory techniques are generally more cognitively demanding.

The selection of appropriate MCDM methods for a given application can vary in how accurate they may be, as well as how much effort is required to perform them [160], [161]. These factors can affect what type of strategy a DM will use [161]. Decision makers tend to gravitate towards minimizing cognitive effort [162], [163]. Some DMs may steer away from using certain selection processes because of the large amount of effort required and instead opt for a simpler technique [162].

Cognitive effort is the total amount of cognitive resources that are needed overall for a decision-making task [164], [165]. A technique considering just one attribute at a time may require less effort and have lower accuracy for some decision problems, than one that takes into account more attributes at a time for calculations [160].

A typical DM would be unwilling to use more cognitive effort than is necessary for the level of confidence that he/she hopes to get for a particular scenario [17]. If the level of confidence required for a decision situation is high or if the importance of the situation is high, then the DM is more likely to use a higher amount of cognitive effort.
Another factor the DM may consider in selecting the MCDM technique is how much time is available for implementation of the project. In scenarios where time is critical, techniques that require less cognitive effort may be preferable, such as EBA or lexicographic methods, to quicken the decision-making process [166]. In less time sensitive situations, the DM would be more willing to make additional effort to get more accurate results using more sophisticated methods [166].

3.2 Step-by-Step Procedure

This section explains the multistage MCDM strategy, used to solve the problem of selecting the best product supplier. The method is flexible in that it can be used for various applications with different accuracy and effort levels depending on the requirements of the given business case. The idea is to select the best material by screening the suppliers from business performance perspective first, followed by a technical material selection problem solving. The first stage, i.e. supplier selection (SS) MCDM, would normally encompass qualitative (and perhaps a few quantitative) criteria; whereas the second stage (material selection MCDM from the screened suppliers) would normally entail quantitative criteria where the alternatives can undergo different mechanical tests. The steps of the proposed process can be seen in Figure 3.1. The process has also been exemplified through a case study in the current research for a business involving insulated skirting products (to be presented in the next Chapter).

Remark: The logic behind the order of decision making in this methodology is as follows. It is common that the number of material options and their suppliers for a target product is fairly large in practice. It would not be feasible to request samples from all the existing suppliers for testing
their materials one by one, especially if the pool of suppliers is large. Hence, some form of ore-screening must take place to reduce the number of selections, e.g. using a set of business criteria under a supplier selection MCDM. Once top suppliers are screened, material samples can be inquired from them and tested. Also, conducting the material and supplier selection problems at the same time would not be recommended analytically, as it would force the DM to compare the business requirement attributes with those of material properties, e.g. during criteria weighting; an example would be when trying to compare a material delivery time from suppliers with the material toughness and figuring out which attribute would be more important.

The proposed methodology is customizable in the sense that the criteria selection can be redefined based on the requirements of a given client. This would be particularly suitable for small companies which do not have high experience to deal with complex decision problems. An example of such customizable criteria is the supplier location. Because Canada is such a large country, location was included in this case study as some local manufacturers are significantly far away and would bring high transportation costs. However, for another imaginary scenario where one may consider international suppliers within a given country, location may not be of primary concern, due to shipment costs being similar. For example, assuming Chinese suppliers only, the costs of freight to Canada will not be very different if the choice of manufacturer was between Tianjin and Beijing. In contrast, if the choice is between suppliers in British Columbia and Ontario, that would meaningfully bring different transportation costs into the decision matrix.
Figure 3-1 Proposed workflow for a decision-making process involving both supplier selection (SS) and material selection (MS)
3.2.1 Step 1: Find potential suppliers:

This can be accomplished by conducting a survey and contacting numerous potential suppliers of the material that has been chosen in the design stage and taking notes about each individual alternative.

3.2.2 Step 2: Creating the SS decision matrix:

The decision matrix represents the alternatives, and attributes and weights with respect to the objective of the problem. This matrix will have two parts; the first part will have the alternatives undergoing a screening with “deal breakers”; for simplicity, the latter can merely have yes-no type of data, where if any of the criteria is not satisfied, then that alternative (supplier) can be discarded. In the second part of the matrix, more qualitative data of verbal form (e.g. Poor, Fair, Good, Very Good, and Excellent) can be used.

3.2.3 Step 3: Choose SS MCDM method:

Depending on the business situation regarding required accuracy and time, different MCDM methods can be used on the alternatives (suppliers) that have passed the screening in step 2. If the overall good performance is required for decision making with high accuracy, then a model that is compensatory, such as the Median Ranking Method, would be appropriate for the application. Otherwise, if it is a time-critical situation and the decision accuracy level is not deemed to be crucial, then a simple noncompensatory model, such as the Lexicographic Method, would be sufficient for the application.

3.2.4 Step 4: Order samples from e.g. the top ranked suppliers:

Select e.g. the top 3 alternatives from the appropriate MCDM technique found in step 3 and then request from them samples of their materials that are available for your product.
3.2.5 Step 5: Test the material samples

According to the criteria selected by a technical DM or designer, conduct the appropriate mechanical, electrical, etc. tests to ensure the properties of the candidate materials map correctly to the final requirements of the product.

3.2.6 Step 6: Creating the MS decision matrix:

This matrix will consist of all the experimental results found in the previous step. Most of the data will be quantitative (e.g. elastic moduli) and a few qualitative (e.g. aesthetics). The decision matrix should represent the material alternatives, design and selection attributes as well as their weights with respect to the final objective and application of the product.

3.2.7 Step 7: Choose MS MCDM method(s):

Depending on the situation regarding required accuracy and time availability, different MCDM may be applied on the alternatives that have been listed in Step 6. If the results accuracy for decision making is critical and ample time is available, then a model that is compensatory, such as the SAW or BWM, will be appropriate for the application. Otherwise, if it is a time-critical situation then a simple noncompensatory model, such as the Lexicographic Method, would be sufficient.

3.2.8 Step 8: Select the final material

Select the top alternative material from the MCDM analysis in the previous step and use it for the product, potentially through partnership with the supplier of that material selected in Step 3. If no satisfactory material is found, the entire process may be re-iterated by considering other options from the pool of potential suppliers found in step 1.
Chapter 4: Case Study

4.1 Background

A distributing company based in Canada supplies the Canadian market with insulated skirting products (Figure 4.1) using material suppliers based in the US. However, recently they have faced higher costs associated with importing products to Canada due to unfavorable exchange rates, lowering competitiveness and the profitability of their business.

![Insulated skirting product](image)

Figure 4-1 Insulated skirting product

Over the past years, Canada has frequently experienced favorable exchange rates (Figure 4.2) with the US which has made importing products relatively cheaper and attractive over local means of production. However, in more recent times, the increases exchange rates have left businesses that exploited the above option with difficulties due to more expensive import costs.
Also, the recent rhetoric over trade wars and new tariffs have made these businesses more anxious with regards to the stability of their international supply streams. Naturally, some of these businesses seek more risk-free options and have opted to shifting their focus on obtaining supplies locally.

However, many smaller businesses cannot afford large consulting firms to assist in this transitional endeavor and neither have experience for this form of complex multiple criteria decision-making problems. Here we intend to use the methodology of Chapter 3 to assist a Canadian company in this decision process as follows.

Figure 4-2 Historical exchange rates for CAD-USD (Data source: Bank of Canada, used according to terms of use)
From preliminary meetings with the company, we defined the MCDM problem constraints as such:

- The product will be made of vinyl (due to its already proven performance);
- The product will be made using extrusion processes (given its simple cross-section profile);
- The product will be preferably supplied by a local manufacturer (to save shipment costs).

In meetings with the company we also determined the in-service performance criteria required for the new product, and mapped them to required material tests as follows.

**Ease of installation:** One of the main concerns for the insulation skirting installers was at least making the new product as easy to deal with as their current product. Their current product could be bent around corners without cracking and the need of cutting new pieces (Figure 4.3). Contractors have enjoyed the current product due to the ability to install it easily with minimum waste. Also, this means that they would be more likely recommend it to their other clients. This service property was determined to be toughness (from material properties point of view) and would be determined by conducting a tensile test on the material samples.

**Impact resistance:** This was important so that if a family is playing e.g. sports around the house or if a pebble is kicked up by the lawnmower and it hits the side of the house, it does not puncture and break the product. This will be determined, from materials property perspective, by using a Gardner impact tester on material samples.
**Aesthetics:** The product should look attractive to customers since it is essentially an aesthetic part of the house. The new product should look at least as good as the current product. This will be tested by conducting a survey and generating a ‘group decision making’ score using the MDL method.

![Image](image.png)

Figure 4-3 How the installed product looks as it is bent around a corner

**Scratch resistant:** If some sharp object is being moved close to the wall during service and is dragged along the side of the wall, it should not leave a scratch on the product. This will be tested, from material performance perspective, by running a scratch test method and finding scores using the MDL method.

**Resistant to weathering:** It is important for the business provider whether or not there will be any degradation of the product once in is installed and exposed to the outdoor environment. To test this property, the samples will be exposed to simulated extreme environmental conditions by
submerging them in water for 24 hours in an environmental testing chamber, and then be tested physically to see if they display differences in density compared with unexposed samples. Methodological details of the identified material tests can be founds in the Appendix A.

**Remark:** Manufacturing cost was not included as part of the decision criteria in this case study as the company was already gaining considerable savings through the replacement of international supplier with local suppliers (i.e. avoiding high exchange rates). The quality and properties of the material itself were of primary concern.

### 4.2 The Decision Making Process

#### 4.2.1 Step 1: Find Potential Suppliers

Following the workflow proposed in Chapter 3, the first step of decision making was formed by searching for plastic manufacturers that operated locally. After the search, a database was created with all the suppliers that could potentially produce the skirting product locally. The contact information of each company was included in the database as well. All the companies were contacted via email initially and then over the phone for further discussions. Overall, dozens of local plastic manufacturers were contacted. Notes were carefully taken according to the criteria required for supplier selection (to be discussed in next step). The companies that did not respond to our inquiries via email were discarded from the analysis.

#### 4.2.2 Step 2: Creating the SS Decision Matrix

The notes taken in step 1 were used to construct the SS decision matrix. The matrix was divided into two parts; the first contained yes-no type of data to help screening the potential suppliers in a simple manner. The criteria for this part were chosen as:
• Material Availability (MA): Whether the suppliers are able to supply the material that was requested; i.e. PVC.

• Technological capability (TC): Whether they have the technical ability to perform extrusion processes.

• Ability to supply amount: Whether they can supply the minimum amount of the material that has been ordered (20,000 feet for each profile).

If any of the criteria for a given supplier receives a “no”, then that company will not be considered in the subsequent decision making. In the second part of the matrix, the verbal criteria (i.e. Poor, Fair, Good, Very Good, andExcellent) were used. The criteria for this part were:

• Geographical Location: Where, nationally, the supplier is located. The closer is it to the distributor location, the better; as the delivery costs will be lower.

• Communication: How quick were the suppliers in responding to inquiries and how thorough were their responses.

• Years in business (YIB): How much experience they have in their area of expertise.

• Willingness: How much interest they showed in the project and partnership. This was assessed e.g. in the form of asking for additional meetings and showing willingness to take part in the design process.

The ensuing decision matrix can be seen in Table 4.1. For the first part, with yes-no data, the screening of the suppliers was performed per Table 4.2. Then, the DM was left with the decision matrix in Table 4.3, which can be used for the final SS decision making using an MCDM technique.
Table 4-1 The Supplier Selection decision matrix

<table>
<thead>
<tr>
<th>Company</th>
<th>MA</th>
<th>TC</th>
<th>Ability to supply amount</th>
<th>Location</th>
<th>Communication</th>
<th>YIB</th>
<th>Willingness</th>
</tr>
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<tr>
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<td>Yes</td>
<td>Yes</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>G</td>
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<td>VG</td>
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P: Poor; F: Fair; G: Good; VG: Very Good; E: Excellent
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<th>Company</th>
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<td>No</td>
<td>Yes</td>
<td>Fail</td>
</tr>
<tr>
<td>P</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Fail</td>
</tr>
<tr>
<td>Q</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Fail</td>
</tr>
<tr>
<td>R</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Fail</td>
</tr>
</tbody>
</table>
### Table 4.3 Decision matrix to be used for SS MCDM

<table>
<thead>
<tr>
<th>Screened Companies</th>
<th>Location</th>
<th>Communication</th>
<th>YIB</th>
<th>Willingness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>G</td>
</tr>
<tr>
<td>C</td>
<td>P</td>
<td>E</td>
<td>VG</td>
<td>E</td>
</tr>
<tr>
<td>D</td>
<td>E</td>
<td>VG</td>
<td>E</td>
<td>VG</td>
</tr>
<tr>
<td>E</td>
<td>P</td>
<td>E</td>
<td>VG</td>
<td>E</td>
</tr>
<tr>
<td>M</td>
<td>VG</td>
<td>VG</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>N</td>
<td>F</td>
<td>E</td>
<td>VG</td>
<td>VG</td>
</tr>
</tbody>
</table>

P: Poor; F: Fair; G: Good; VG: Very Good; E: Excellent

#### 4.2.3 Step 3: Choose SS MCDM Method

If the results required for SS decision making should be highly accurate and time is available, then a model that is compensatory, such as the Median Ranking Method, would be suitable. Otherwise, if it is a time-critical situation, then a simple noncompensatory model such as the Lexicographic Method may be sufficient for the application. For this case study, both methods were used to demonstrate whether they would differ in their decisions.

**Scenario 1:** In this scenario, the noncompensatory lexicographic method was tested. The attributes were determined to be in the order of importance of:

- Years in Business
- Location
- Willingness
- Communication
Using the lexicographic method [8], the alternatives can be screened using the most important criterion first, and the most effective alternative(s) are accordingly selected. If there is a tie between two or more alternatives, then these alternatives are compared under the next important criterion; and this process continues until the best one is selected or comparisons have been made under all of the criteria. For the current application, the Lexicographic process for the decision matrix can be seen in Table 4.4. For the suggested most important criterion by the distributor, years in business, the best alternatives are found to be companies A, D and M that are tied.

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Communication</th>
<th>Years in Business</th>
<th>Willingness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>G</td>
</tr>
<tr>
<td>D</td>
<td>E</td>
<td>VG</td>
<td>E</td>
<td>VG</td>
</tr>
<tr>
<td>M</td>
<td>VG</td>
<td>VG</td>
<td>E</td>
<td>E</td>
</tr>
</tbody>
</table>

P: Poor; F: Fair; G: Good; VG: Very Good; E: Excellent

At this stage, we already found the top 3 companies that we were searching for and the SS decision process can end. It can be seen that the Lexicographic method is quick and easy to implement for decision making; however it does not give detailed ranking of the alternatives.

**Scenario 2:** In this scenario, given the time for project implementation it would be best to apply a compensatory technique, i.e. here the median ranking method. As explained in Chapter 2
(section 2.2.11), in this method the first step is to obtain ranks from the given data. When there is a tie between two options, then the alternatives that are tied should receive an average rank. The decision matrix of Table 4.3 will translate to the ranks shown in Table 4.5.

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Communication</th>
<th>YIB</th>
<th>Willingness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.5</td>
<td>2.5</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>C</td>
<td>5.5</td>
<td>2.5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>1.5</td>
<td>5.5</td>
<td>2</td>
<td>4.5</td>
</tr>
<tr>
<td>E</td>
<td>5.5</td>
<td>2.5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>M</td>
<td>3</td>
<td>5.5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>N</td>
<td>4</td>
<td>2.5</td>
<td>5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Next, the importance of the attributes were determined using the Modified Digital Logic approach with direct input from the client; results can be found in Table 4.6. The MDL considers predominance of one criterion to another at a time and hence it is simple to implement for non-expert DMs. The comparison was made sequentially in a pairwise manner in order to learn the preference of one criterion over another until all the criteria comparisons were fulfilled.

<table>
<thead>
<tr>
<th>Goals</th>
<th>Number of Possible Decisions</th>
<th>Positive Decisions</th>
<th>Weighting Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>3 1 3</td>
<td>7</td>
<td>0.292</td>
</tr>
<tr>
<td>Communication</td>
<td>1 1 1</td>
<td>3</td>
<td>0.125</td>
</tr>
<tr>
<td>YIB</td>
<td>3 3 3</td>
<td>9</td>
<td>0.375</td>
</tr>
<tr>
<td>Willingness</td>
<td>1 3 1</td>
<td>5</td>
<td>0.208</td>
</tr>
</tbody>
</table>
Now that the DM attains the criteria ranks and the weights, we can use the following equation 2.19 to determine the total distance of each alternative: \( d_{ik} = \sum_{j=1}^{n} w_j |s_{ij} - k| \).

For the first alternative A, e.g. one can calculate the rank distances as:

\[
\begin{align*}
    d_{A1} &= 0.292|1.5 - 1| + 0.125|2.5 - 1| + 0.375|2 - 1| + 0.208|6 - 1| = 1.75 \\
    d_{A2} &= 0.292|1.5 - 2| + 0.125|2.5 - 2| + 0.375|2 - 2| + 0.208|6 - 2| = 1.04 \\
    d_{A3} &= 0.292|1.5 - 3| + 0.125|2.5 - 3| + 0.375|2 - 3| + 0.208|6 - 3| = 1.50 \\
    d_{A4} &= 0.292|1.5 - 4| + 0.125|2.5 - 4| + 0.375|2 - 4| + 0.208|6 - 4| = 2.08 \\
    d_{A5} &= 0.292|1.5 - 5| + 0.125|2.5 - 5| + 0.375|2 - 5| + 0.208|6 - 5| = 2.67 \\
    d_{A6} &= 0.292|1.5 - 6| + 0.125|2.5 - 6| + 0.375|2 - 6| + 0.208|6 - 6| = 3.25
\end{align*}
\]

For alternative C:

\[
\begin{align*}
    d_{C1} &= 0.292|5.5 - 1| + 0.125|2.5 - 1| + 0.375|5 - 1| + 0.208|2 - 1| = 3.21 \\
    d_{C2} &= 0.292|5.5 - 2| + 0.125|2.5 - 2| + 0.375|5 - 2| + 0.208|2 - 2| = 2.21 \\
    d_{C3} &= 0.292|5.5 - 3| + 0.125|2.5 - 3| + 0.375|5 - 3| + 0.208|2 - 3| = 1.75 \\
    d_{C4} &= 0.292|5.5 - 4| + 0.125|2.5 - 4| + 0.375|5 - 4| + 0.208|2 - 4| = 1.42 \\
    d_{C5} &= 0.292|5.5 - 5| + 0.125|2.5 - 5| + 0.375|5 - 5| + 0.208|2 - 5| = 1.08 \\
    d_{C6} &= 0.292|5.5 - 6| + 0.125|2.5 - 6| + 0.375|5 - 6| + 0.208|2 - 6| = 1.79
\end{align*}
\]

For alternative D:

\[
\begin{align*}
    d_{D1} &= 0.292|1.5 - 1| + 0.125|5.5 - 1| + 0.375|2 - 1| + 0.208|4.5 - 1| = 1.81
\end{align*}
\]
\[ d_{D2} = 0.292|1.5 - 2| + 0.125|5.5 - 2| + 0.375|2 - 2| + 0.208|4.5 - 2| = 1.10 \]
\[ d_{D3} = 0.292|1.5 - 3| + 0.125|5.5 - 3| + 0.375|2 - 3| + 0.208|4.5 - 3| = 1.44 \]
\[ d_{D4} = 0.292|1.5 - 4| + 0.125|5.5 - 4| + 0.375|2 - 4| + 0.208|4.5 - 4| = 1.77 \]
\[ d_{D5} = 0.292|1.5 - 5| + 0.125|5.5 - 5| + 0.375|2 - 5| + 0.208|4.5 - 5| = 2.31 \]
\[ d_{D6} = 0.292|1.5 - 6| + 0.125|5.5 - 6| + 0.375|2 - 6| + 0.208|4.5 - 6| = 3.19 \]

For alternative E:
\[ d_{E1} = 0.292|5.5 - 1| + 0.125|2.5 - 1| + 0.375|5 - 1| + 0.208|2 - 1| = 3.21 \]
\[ d_{E2} = 0.292|5.5 - 2| + 0.125|2.5 - 2| + 0.375|5 - 2| + 0.208|2 - 2| = 2.21 \]
\[ d_{E3} = 0.292|5.5 - 3| + 0.125|2.5 - 3| + 0.375|5 - 3| + 0.208|2 - 3| = 1.75 \]
\[ d_{E4} = 0.292|5.5 - 4| + 0.125|2.5 - 4| + 0.375|5 - 4| + 0.208|2 - 4| = 1.42 \]
\[ d_{E5} = 0.292|5.5 - 5| + 0.125|2.5 - 5| + 0.375|5 - 5| + 0.208|2 - 5| = 1.08 \]
\[ d_{E6} = 0.292|5.5 - 6| + 0.125|2.5 - 6| + 0.375|5 - 6| + 0.208|2 - 6| = 1.79 \]

For alternative M:
\[ d_{M1} = 0.292|3 - 1| + 0.125|5.5 - 1| + 0.375|2 - 1| + 0.208|2 - 1| = 1.73 \]
\[ d_{M2} = 0.292|3 - 2| + 0.125|5.5 - 2| + 0.375|2 - 2| + 0.208|2 - 2| = 0.73 \]
\[ d_{M3} = 0.292|3 - 3| + 0.125|5.5 - 3| + 0.375|2 - 3| + 0.208|2 - 3| = 0.90 \]
\[ d_{M4} = 0.292|3 - 4| + 0.125|5.5 - 4| + 0.375|2 - 4| + 0.208|2 - 4| = 1.65 \]
\[ d_{M5} = 0.292|3 - 5| + 0.125|5.5 - 5| + 0.375|2 - 5| + 0.208|2 - 5| = 2.40 \]
\[ d_{M6} = 0.292|3 - 6| + 0.125|5.5 - 6| + 0.375|2 - 6| + 0.208|2 - 6| = 3.27 \]
For alternative N:

\[ d_{N1} = 0.292|4 - 1| + 0.125|2.5 - 1| + 0.375|5 - 1| + 0.208|4.5 - 1| = 3.29 \]

\[ d_{N2} = 0.292|4 - 2| + 0.125|2.5 - 2| + 0.375|5 - 2| + 0.208|4.5 - 2| = 2.29 \]

\[ d_{N3} = 0.292|4 - 3| + 0.125|2.5 - 3| + 0.375|5 - 3| + 0.208|4.5 - 3| = 1.42 \]

\[ d_{N4} = 0.292|4 - 4| + 0.125|2.5 - 4| + 0.375|5 - 4| + 0.208|4.5 - 4| = 0.67 \]

\[ d_{N5} = 0.292|4 - 5| + 0.125|2.5 - 5| + 0.375|5 - 5| + 0.208|4.5 - 5| = 0.71 \]

\[ d_{N6} = 0.292|4 - 6| + 0.125|2.5 - 6| + 0.375|5 - 6| + 0.208|4.5 - 6| = 1.71 \]

The summary of these distances can be expressed in the matrix form as:

\[
\begin{bmatrix}
1st & 2nd & 3rd & 4th & 5th & 6th \\
A & 1.75 & 1.04 & 1.50 & 2.08 & 2.67 & 3.25 \\
C & 3.21 & 2.21 & 1.75 & 1.42 & 1.08 & 1.79 \\
D & 1.81 & 1.10 & 1.44 & 1.77 & 2.31 & 3.19 \\
E & 3.21 & 2.21 & 1.75 & 1.42 & 1.08 & 1.79 \\
M & 1.73 & 0.73 & 0.90 & 1.65 & 2.40 & 3.27 \\
N & 3.29 & 2.29 & 1.42 & 0.67 & 0.71 & 1.71
\end{bmatrix}
\]

Next, the Hungarian Method was used to assign the ranks to each alternative, based on the following steps [8]:

Step 1: Row Reduction. Subtract the minimum value of each row from all the values in that row.
### Step 2: Column Reduction

Subtract the minimum value of each column from all values in the column.

<table>
<thead>
<tr>
<th></th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.71</td>
<td>0</td>
<td>0.46</td>
<td>1.04</td>
<td>1.63</td>
<td>2.21</td>
</tr>
<tr>
<td>C</td>
<td>2.13</td>
<td>1.13</td>
<td>0.67</td>
<td>0.34</td>
<td>0</td>
<td>0.71</td>
</tr>
<tr>
<td>D</td>
<td>0.71</td>
<td>0</td>
<td>0.34</td>
<td>0.67</td>
<td>1.21</td>
<td>2.09</td>
</tr>
<tr>
<td>E</td>
<td>2.13</td>
<td>1.13</td>
<td>0.67</td>
<td>0.34</td>
<td>0</td>
<td>0.71</td>
</tr>
<tr>
<td>M</td>
<td>1</td>
<td>0</td>
<td>0.17</td>
<td>0.92</td>
<td>1.67</td>
<td>2.54</td>
</tr>
<tr>
<td>N</td>
<td>2.62</td>
<td>1.62</td>
<td>0.75</td>
<td>0</td>
<td>0.04</td>
<td>1.04</td>
</tr>
</tbody>
</table>

### Step 3: Cover the Zeros

Draw the smallest number of lines that will cover all zeros.

<table>
<thead>
<tr>
<th></th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>0</td>
<td>0.29</td>
<td>1.04</td>
<td>1.63</td>
<td>1.50</td>
</tr>
<tr>
<td>C</td>
<td>1.42</td>
<td>1.13</td>
<td>0.50</td>
<td>0.34</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>0</td>
<td>0.17</td>
<td>0.67</td>
<td>1.21</td>
<td>1.38</td>
</tr>
<tr>
<td>E</td>
<td>1.42</td>
<td>1.13</td>
<td>0.50</td>
<td>0.34</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M</td>
<td>0.29</td>
<td>0</td>
<td>0</td>
<td>0.92</td>
<td>1.67</td>
<td>1.83</td>
</tr>
<tr>
<td>N</td>
<td>1.91</td>
<td>1.62</td>
<td>0.58</td>
<td>0</td>
<td>0.04</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Since it takes 6 lines to cover all of the zeros, an optimal solution can be found and there is no need to create new zeros.

Step 4: Make assignments; the assignments can be seen as highlights below.

Finally, this method could rank the alternatives from first to last. From the Median Ranking results from step 4, we find that the top 3 suppliers are the companies A, then D and then M.
4.2.4 Step 4: Order material samples from the top 3 suppliers

Since the solutions from the above analyses both suggested A, D, and M companies, we contacted these companies to request material samples, to be used for testing.

4.2.5 Step 5: Test samples

In this step we should look for results for the material tests that were determined by the DM in Step 2. The tests were conducted on samples sent from companies A, D and M and were compared with the current supplier’s product, which is referred to as ‘control’ hereafter.

**Tensile testing:** Results from the tensile tests were used to determine the toughness of the material samples. Toughness is the ability of a material to absorb energy, plastically deform and resist fracturing when force is applied. This can be determined by calculating the total area up to fracture under a stress-strain curve. The average toughness of the three repeats will be fed into the subsequent MS MCDM for the decision making.

At the peak stress point the material begins to undergo damage but the final failure occurs later. The failure point was determined visually at the point where the test specimen begins to split apart. Due to various reasons such as micro-cracks in the material, the repeats of each material do not fail (break) at the same exact strain point. This is the reason for the large error bars seen in Figure 4.4; i.e. close to the end of each curve (after failure), the standard deviation becomes very large. A comparison of materials before the final breakage can be seen in Figure 4.5. This graph contains the curves of the samples until the first point of failure (shown as circles in Figure 4.4). As such, here we get a more clear comparison of the materials, and under reasonable error levels.
Figure 4-4 Stress versus strain response of the material samples from top ranked suppliers. The circles represent the earliest (weakest) breakage points among the test repeats of a given company material.

Figure 4-5 Stress and strain response of the material samples before the failure points of the weakest repeat.
Here we can see that the error bars for each of the materials except for Company D are fairly small. It is clear from the above results that on average all the top three suppliers can provide a material with superior toughness compared to the current product. Namely, the toughness values of Control, A, D, M options were measured (using the under curve areas upon to the final points of the curves then averaged) to be 3.15, 39.35, 15.69, and 9.82 J/m$^3$, respectively.

**Scratch resistance testing:** The results from the scratching tests were as follows.

For samples of company A:
- A scratches M
- A does not scratch D
- A does not scratch Control

For samples of company D:
- D scratches M;
- D scratches A;
- D does not scratch the Control.

For samples of company M:
- M does not scratch D;
- M does not scratch A;
- M does not scratch the Control

For the control samples:
- Control scratches M
- Control scratches A
• Control does not scratch D

From the results above, the DM can conclude that the D and the Control samples are the most scratch resistant and have similar surface hardness. Next preference under this criterion would be company M and in the last place is company A. The DM can use the MDL with the above results in order to generate ‘numerical scores’ of these alternatives, as seen in Table 4.7 below.

Table 4.7 Numerical results of the scratch resistance test using MDL method

<table>
<thead>
<tr>
<th>Options</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Positive decisions</th>
<th>Weights (scores)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td></td>
<td>8</td>
<td></td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>0.21</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td>0.33</td>
</tr>
<tr>
<td>M</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>0.13</td>
</tr>
</tbody>
</table>

**Impact testing:** The results from the impact tests for the Control, Company A, Company D and Company M samples can be seen in Figures 4.6, 4.7, 4.8 and 4.9, respectively. Mean failure height \( h \) parameter in each test (also see the Appendix A) was calculated using equation 4.1:

\[
h = h_0 + d_h \left( \frac{A}{N} \pm 0.5 \right)
\]  

(4.1)

Where, \( d_h \) is increment of weight heights (here 25 mm); \( N \) is the total number of failure or non-failure “events” (whichever smaller), \( h_0 \) (in mm) is the lowest height at which an event occurred.

The value of \( A \) can be calculated via:

\[
A = \sum_{t=0}^{k} n_t
\]

(4.2)
Where, \( i = 0, 1, 2 \ldots k \) (counting index, starts at \( h_0 \)); \( n_i \) is the number of events that occurred at \( h_i \).

The negative sign is used when the events are failures and the positive sign when the events are non-failures. Mean failure energy (MFE) can be calculated using:

\[
MFE = \frac{h \times m \times g}{1000} \quad (4.3)
\]

Where, \( h \) is the mean failure height in mm, \( m \) is the mass used for the test (here 2 kg), and \( g \) is the gravity (9.81 N/kg). For each case, to determine the starting point, a test is conducted on the material by dropping the weight at the lowest height then incrementally increasing the height until the first failure occurs. This point is then selected as the starting point for the actual test.

<table>
<thead>
<tr>
<th>Height (mm)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>75</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

\[
A = (0 \times 6) + (1 \times 3) = 3; \quad h = 75 + 25\left(\frac{3}{9} - 0.5\right) = 70.83 \text{ mm}
\]

\[
MFE = \frac{70.83 \times 2 \times 9.81}{1000} = 1.39 \text{ J}
\]

Figure 4-6 Test results for the impact test of the Control material
A = (0 × 1) + (1 × 3) + (2 × 5) = 13; 
\[ h = 75 + 25 \left( \frac{13}{9} - 0.5 \right) = 98.61 \text{ mm} \]
\[ \text{MFE} = \frac{98.61 \times 2 \times 9.81}{1000} = 1.93 \text{ J} \]

Figure 4-7 Test results for the impact test of the Company A material

\[ A = (0 \times 8) + (1 \times 1) = 1; \]
\[ h = 150 + 25 \left( \frac{\frac{1}{9} - 0.5}{9} \right) = 140.27 \text{ mm} \]
\[ \text{MFE} = \frac{140.27 \times 2 \times 9.81}{1000} = 2.75 \text{ J} \]

Figure 4-8 Test results for the impact test of the Company D material
Weathering resistance testing: The test values as a percentage of density change in the sample due to environmental exposure can be seen in Table 4.8.

Table 4-8 Test results of density change % of different material samples under weathering test

<table>
<thead>
<tr>
<th>Company</th>
<th>Density Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.01</td>
</tr>
<tr>
<td>A</td>
<td>3.45</td>
</tr>
<tr>
<td>D</td>
<td>8.46</td>
</tr>
<tr>
<td>M</td>
<td>2.52</td>
</tr>
</tbody>
</table>
From the table above, the DM can see that the control product would be the most suited for resisting weathering as it had minimal change in material density; whereas the sample from Company D performed the worst with a density change as high as 8.46%.

**Aesthetics testing:** Aesthetics of the sample materials were rated by conducting a survey where a group of engineers at CRN Okanagan Laboratory compared the candidates in a pairwise manner and selected which one in each pair would be more appealing aesthetically if installed on the side of a residential building. Then, the Modified Digital Logic (MDL) method was used to generate the final scores of alternatives. The results of the aesthetics test (Table 4.9) suggested that the Control would be the best option with a score of 0.306. Company A was a close second option with a score of 0.296; and companies D and M were ranked third and fourth with scores of 0.231 and 0.167, respectively.

<table>
<thead>
<tr>
<th>Company</th>
<th>Average Score</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.306</td>
<td>0.088</td>
</tr>
<tr>
<td>A</td>
<td>0.296</td>
<td>0.073</td>
</tr>
<tr>
<td>D</td>
<td>0.231</td>
<td>0.089</td>
</tr>
<tr>
<td>M</td>
<td>0.167</td>
<td>0.047</td>
</tr>
</tbody>
</table>

4.2.6 **Step 6: Create the MS decision matrix**

All the test results from step 5 were compiled together to construct the MS decision matrix as seen in Table 4.10.
Table 4-10 The material selection (MS) decision matrix; +/- signs indicate the higher the better, or the low the better type of criteria, respectively

<table>
<thead>
<tr>
<th>Material Options</th>
<th>Toughness (J/m³) (+)</th>
<th>Impact MFE (J) (+)</th>
<th>Density Change (%) (-)</th>
<th>Scratch Resistance (+)</th>
<th>Aesthetics (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>3.15</td>
<td>1.39</td>
<td>0.00</td>
<td>0.33</td>
<td>0.31</td>
</tr>
<tr>
<td>A</td>
<td>39.35</td>
<td>1.93</td>
<td>3.45</td>
<td>0.21</td>
<td>0.30</td>
</tr>
<tr>
<td>D</td>
<td>15.69</td>
<td>2.75</td>
<td>8.46</td>
<td>0.33</td>
<td>0.23</td>
</tr>
<tr>
<td>M</td>
<td>9.82</td>
<td>9.14</td>
<td>2.52</td>
<td>0.13</td>
<td>0.17</td>
</tr>
</tbody>
</table>

One of the main assumptions of a MCDM problems is that the criteria are independent [166], meaning that one criterion’s variation due to different alternatives is independent from the other criteria. We can check this assumption by statistically testing the correlation values between the criteria pairs, which can be calculated by using equation 4.4. The correlation matrix and corresponding P-values are reported in Table 4.11 and Table 4.12, respectively

\[ r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \]  

(4.4)

Table 4-11 The correlation matrix of the MS criteria

<table>
<thead>
<tr>
<th></th>
<th>Toughness</th>
<th>Impact</th>
<th>Density Change</th>
<th>Scratch Resistance</th>
<th>Aesthetics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughness</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact</td>
<td>-0.2668</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density Change</td>
<td>0.285945</td>
<td>0.04989</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scratch Resistance</td>
<td>-0.26865</td>
<td>0.79602</td>
<td>0.226468</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Aesthetics</td>
<td>0.291011</td>
<td>0.92553</td>
<td>-0.30096</td>
<td>0.585206</td>
<td>1</td>
</tr>
</tbody>
</table>
### Table 4-12 The P-values (statistical significance) of the calculated correlations of the MS criteria

<table>
<thead>
<tr>
<th></th>
<th>Toughness</th>
<th>Impact (J)</th>
<th>Density Change</th>
<th>Scratch Resistance</th>
<th>Aesthetics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughness</td>
<td>-</td>
<td>0.7332</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Impact (J)</td>
<td>0.7141</td>
<td>0.9501</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Density Change</td>
<td>0.7314</td>
<td>0.2040</td>
<td>0.7735</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Scratch Resistance</td>
<td>0.7090</td>
<td>0.0745</td>
<td>0.6990</td>
<td>0.4148</td>
<td></td>
</tr>
<tr>
<td>Aesthetics</td>
<td>0.7090</td>
<td>0.0745</td>
<td>0.6990</td>
<td>0.4148</td>
<td>-</td>
</tr>
</tbody>
</table>

The P-Values of all the correlations are greater than 0.05, indicating no statistical significance. Hence, we can assume that all of the criteria in the given case are independent from one another.

#### 4.2.7 Step 7: Choose the MS MCDM method

Similar to the case during the choosing of the SS MCDM method (section 4.2.3), if high accuracy of decision results are required for DM along with available time, then a model that is compensatory, such as the Best-Worst Method with SAW, can be used in the present case. Otherwise, if it is a time-critical situation then a simple noncompensatory model, such as the Lexicographic Method, would be suitable. For this part of the case study, both methods will be used to demonstrate their differences.

**Scenario 1:** In this scenario, the DM chooses to apply the noncompensatory lexicographic method. The MS attributes were determined to be in the order of importance of:

- Toughness
- Aesthetics
- Impact Resistance
- Scratch Resistance
- Weathering (density change)

Using the lexicographic method, the alternatives were screened using the most important criterion first, and if there is a tie between two or more alternatives, then they are compared under the next important criterion; and this process continues until the best one is selected or comparisons have been made under all the criteria. Starting from the decision matrix in Table 4.10, the lexicographic approach using the most important criterion, toughness, made Company A as the sole best option, having the highest toughness value.

**Scenario 2:** In this scenario, the DM opts to apply a compensatory technique, in this case, the Best-Worst Method (BWM) in order to determine the weights accurately and combined them with the SAW MCDM for the final decision making.

Under a linear programming as described in section 2.2.12., in the BWM, the best and worst criteria are selected first. Pairwise comparisons are made where the best criterion is compared with the other criteria and then other criteria are compared to the worst criterion. The weights of the criteria are determined using an optimization model.

Similar to scenario 1, toughness and density change have been selected as the best and worst criteria, respectively (Table 4.13). The Best-to-Others comparisons can be seen in Table 4.14 and the Others-to-Worst comparisons can be seen in Table 4.15.
Table 4-13 The best and worst material criteria selected for the BW method

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Name</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best (most important)</td>
<td>Toughness</td>
<td>Allows for increased ease of installation making it preferable to contractors.</td>
</tr>
<tr>
<td>Worst (least important)</td>
<td>Density Change</td>
<td>The climate in Kelowna is very mild and does not go through extreme weather changes.</td>
</tr>
</tbody>
</table>

Table 4-14 The Best-to-Others comparisons in the BWM

<table>
<thead>
<tr>
<th>Best to Others</th>
<th>Toughness</th>
<th>Impact</th>
<th>Density Change</th>
<th>Scratch Resistance</th>
<th>Aesthetics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best: Toughness</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4-15 The Others-to-Worst comparisons in the BWM

<table>
<thead>
<tr>
<th>Others to Worst</th>
<th>Worst: Density Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughness</td>
<td>6</td>
</tr>
<tr>
<td>Impact</td>
<td>4</td>
</tr>
<tr>
<td>Density Change</td>
<td>1</td>
</tr>
<tr>
<td>Scratch Resistance</td>
<td>3</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>5</td>
</tr>
</tbody>
</table>

The weights that were determined by solving the BWM equations (using Microsoft Excel’s solver function) can be found in Figure 4.16, with a inconsistency factor of $\xi_L^* = 0.095$. As stated previously, $\xi_L$ can be considered as an indicator of inconsistency in the BWM; the closer its value is to zero, the higher is the consistency of obtained weights (in the current case: 1-0.095, i.e. over 90% consistency).
Table 4-16 Weights generated from the BWM

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Toughness</th>
<th>Impact</th>
<th>Density Change</th>
<th>Scratch Resistance</th>
<th>Aesthetics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights</td>
<td>0.43</td>
<td>0.13</td>
<td>0.06</td>
<td>0.11</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Finally, for using the SAW method to obtain the final rank of the materials, since the data in table 4.10 are of different units and they cannot be summed, a data normalization is required to obtain a common scale. Linear normalization is the most commonly used method in conjunction with SAW [8]. It is implemented simply by dividing the value of each criterion to its maximum value. The result of this normalization and SAW can be seen in Table 4.17 and 4.18, respectively.

Table 4-17 Results of the linear normalization of MS data

<table>
<thead>
<tr>
<th></th>
<th>Toughness</th>
<th>Impact</th>
<th>Density Change</th>
<th>Scratch Resistance</th>
<th>Aesthetics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.08</td>
<td>0.15</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>0.21</td>
<td>0.41</td>
<td>0.64</td>
<td>0.97</td>
</tr>
<tr>
<td>D</td>
<td>0.40</td>
<td>0.30</td>
<td>1</td>
<td>1</td>
<td>0.74</td>
</tr>
<tr>
<td>M</td>
<td>0.25</td>
<td>1</td>
<td>0.30</td>
<td>0.40</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 4-18 The result of SAW material selection

<table>
<thead>
<tr>
<th></th>
<th>Toughness</th>
<th>Impact</th>
<th>Density Change</th>
<th>Scratch Resistance</th>
<th>Aesthetics</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.04</td>
<td>0.02</td>
<td>0</td>
<td>0.11</td>
<td>0.27</td>
<td>0.43</td>
</tr>
<tr>
<td>A</td>
<td>0.44</td>
<td>0.03</td>
<td>0.02</td>
<td>0.07</td>
<td>0.26</td>
<td>0.77</td>
</tr>
<tr>
<td>D</td>
<td>0.17</td>
<td>0.04</td>
<td>0.06</td>
<td>0.11</td>
<td>0.20</td>
<td>0.46</td>
</tr>
<tr>
<td>M</td>
<td>0.11</td>
<td>0.13</td>
<td>0.02</td>
<td>0.04</td>
<td>0.15</td>
<td>0.41</td>
</tr>
</tbody>
</table>
4.2.8 Step 8: Select the final material supplier

From Table 4.19, the DM can find that the best material is from Company A. It would be by far an optimum decision to select A as the new material and supplier. The materials from suppliers D and M have performed overall very closely to the Control, and may be considered as secondary options.

Table 4-19 Ranking of the SAW results for the candidate materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Score</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.43</td>
<td>3</td>
</tr>
<tr>
<td>A</td>
<td>0.77</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>0.4</td>
<td>2</td>
</tr>
<tr>
<td>M</td>
<td>0.41</td>
<td>4</td>
</tr>
</tbody>
</table>
Chapter 5: **Conclusions and Recommendations**

### 5.1 Summary and Conclusions

A distribution company based in Canada supplies the local market with insulated skirting product. The company had faced problems with their current material supplier overseas and wanted to shift to a local supplier. Locally, there were a large number of options that could be a candidate supplier. The key was to find a systematic way to screen the alternatives and select the optimum one according to the company’s both business and technical requirements. As a consequence of changing the supplier, the material of the skirting product may also face some changes, in terms of mechanical properties. Hence, material selection was deemed to be crucial for the success of this strategic decision making by the company.

A customizable, multi-stage MCDM methodology was developed in this research to compare numerous suppliers and their materials using a hybrid of compensatory and non-compensatory, as well as qualitative and quantitative decision models. The methodology is customizable in the sense that the criteria in the decision matrix highly depend on the scenarios surrounding the SME client; where different users can adapt different set of criteria depending on the product and business case. All the decision criteria were first identified during meetings with the company staff. Constraints (or must-fully-satisfy criteria) were also identified and included in the case study. Alternatives were initially screened on these constraints, and only feasible alternatives were kept in the subsequent MCDM implementation. During MCDM, suppliers were first scored in the Supplier Selection stage using a number of business-oriented criteria (Years in Business, Location, Willingness, and Communication). Subsequently the top 3 companies were requested
to send material samples. Then, in the Material Selection phase, these samples were tested according to the predetermined set of mechanical and aesthetics performance attributes, and finally the supplier with the highest overall score was selected. The latter criteria in the order of DM preference included: toughness, aesthetics, impact resistance, scratch resistance and weathering. Also, the independence of these criteria was tested using a correlation analysis. For a compensatory MCDM solution, which next to ranking clearly showed the relative scores of the alternatives, the criteria weights were determined using the MDL and BWM methods, for Supplier Selection and Material Selection phases, respectively. For a non-compensatory MCDM solution, however, no criteria weights were required, hence simpler and faster to implement but at the cost of losing decision accuracy.

5.2 Limitations of the Work

One of the motivations behind the selection of the MCDM techniques for this research was the ease of implementation for the general (non-expert) end users, especially for SMEs. Simplistic and intuitive techniques would result in more likely application of the methodology. However, the presented methodology was designed for a single DM only, and not under a group MCDM. Another limitation was that all the candidate suppliers did not have the same manufacturing abilities. Namely, the control product (with a given shape and dimensions) was textured and that contributed to its unusually high score under the aesthetics criteria. Although, the other companies could conduct extrusion and make the correct shape and profile of the skirting product as the control, they were not equipped to form any surface texturing. Another limitation was not including UV testing in the weathering resistance assessment.
5.3 **Recommendations for Future Work**

The following recommendations may be proposed as future directions of the research:

- The methodology can be adapted to account for group decision making environments.
- The methodology can be expanded to include different shapes and sizes of the product, which may have different set of functionalities/criteria.
- Different manufacturing methods and their factors including cost could be added in the decision making.
- In weathering tests, one can conduct some form of accelerated UV testing to test the materials on their ability to resist UV degradation, as applicable for outdoor applications.
- Applications other than insulated skirting may be tested against the proposed methodology.
- The future work could also involve more complex decision approaches that employ e.g. fuzzy numbers in the decision making process.
Bibliography


Appendices

Appendix A : Experimental Tests Used in this Study

A.1  Tensile Test

The tensile test was used in order to generate the load-extension curves of the candidate materials. The specimens were prepared according to ASTM D638 and the dimensions can be seen in Figure A-1.

![Figure A-1 Dimensions used for the tensile test specimens](image)

The DXF files of the specimens were created using SolidWorks and was cut into shape using water jet cutting; a sample specimen can be seen in Figure A-2. For the experiment, the width and thickness were measured using a Vernier caliper. Then, the specimen were placed in the grips of the INSTRON 5969, as seen in Figure A-3. The speed of testing was set at 5 mm/min and 3 repeats of the test were conducted for each material.
A.2 **Scratch Resistance Test**

Scratch resistance of materials surface was determined by comparing their relative hardness against each other. Namely, the specimens used in this test are simple square pieces that have
sharp corners and are cut to shape using water jet cutting; Figure A-4. This test is conducted by placing the sharp corner of one specimen on the flat surface of another and attempting to scratch it.

Figure A-4 Example of specimens used for the scratch resistance test. Left piece is used to scratch the right piece

The scenarios that encountered may be one of the following:

- If Specimen 1 scratches Specimen 2, then Specimen 1 is harder than Specimen 2.
- If Specimen 1 cannot scratch Specimen 2, then Specimen 2 is harder than Specimen 1.
- If the two specimen cannot scratch each other, then Specimen 1 and Specimen 2 have equal hardness.
- If Specimen 1 can be scratched by Specimen 2 but not by Specimen 3, then Specimen 1 has a hardness between that of Specimen 2 and Specimen 3.
This method is ideal for a study that involves a limited set of alternatives as the pairwise comparisons will be significantly large as the number of alternatives increases.

**A.3 Impact Test**

This test was conducted according to ASTM D4226 in order to determine the impact energy required for the samples to fail due to impact. Using the Gardner Impact tester, PF-5545 model, the mass of 2 kg was used. The setup is shown in Figure A-5. A total of 20 impacts were made and the Up-and Down Method was used with the recorded data. This will allow for the Mean Failure Height to be determined, as follows:

- Raise the weight and the impactor and place the specimen flat on the anvil so that it covers the hole.
- If the estimated failure energy is not known, then run a series of impact tests at different heights in order to capture the failure onset.
- Place the impactor on the specimen and raise the weight to the estimated failure energy and release it so that it strikes the impactor.
- Remove the specimen and check to see if it has failed. If it did not fail, then increase the height of the weight by one increment or if it did fail then decrease the height by one increment and test again at another point on the specimen.
- Mark failures with an “f” and non-failures with a “p”.
A.4 Weathering Resistance

In order to understand the effect of the environmental condition on the specimens, their densities were tested before and after exposure to moisture and temperature variation. The square specimen with 25 mm lengths (Figure A-6) were placed in a Thermotron Environmental Chamber, seen in Figure A-7, and were conditioned according to ASTM D618 with the samples being submerged in water at 23 °C for 24 hours.
A.5 Aesthetics

Aesthetics of the samples was determined via pair-wise comparisons in a survey among expert engineers at UBC CRN Okanagan laboratory. Here, participants compared materials two at a time and determined if they would prefer one over another or would find them equally appealing aesthetically. The preferences were recorded and scores for each material were then generated using the Modified Digital Logic method [27].