A MULTI-CRITERIA DECISION ANALYSIS APPROACH TO PALLET SELECTION: DEVELOPMENT OF A MATERIAL-OF-CONSTRUCTION EVALUATION MODEL

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ABSTRACT

Although pallets have traditionally been constructed from wood, there has been a shift towards making them from plastic and other composite materials. Subsequently, the storage and transportation industry has been inundated with questions about ‘the best’ pallet material type in relation to a supply chain. In addition, in a rapidly changing global manufacturing and storage environment, industry players have difficulty justifying the high capital cost of adopting new state-of-the-art pallets. This paper seeks to build a model to identify the best pallet material-of-construction (MOC) as perceived by the end consumer. The approach used for this was based on different stages of building an assistive multi-criteria decision model. This included modelling the decision framework using the analytic hierarchy process and undertaking an independent case study as the baseline for the modelling.

OPSOMMING

Alhoewel palette tradisioneel van hout gemaak is, was daar 'n verskuiwing om dit van plastiek en ander saamgestelde materiale te maak. Daarna is die berging- en vervoerbedryf oorval met vrae oor 'die beste' paletmateriaaltipe met betrekking tot 'n voorsieningsketting. Boonop, in 'n vinnig veranderende wêreldwye vervaardiging- en bergingsomgewing, sukkel rolspelers in die industrie om die hoë kapitaalkoste van die aanvaarding van nuwe, moderne palette te regverdig. Hierdie artikel poog om ’n model te bou om die beste paletkonstruksiemateriaal te identifiseer soos deur die eindverbruiker waargeneem. Die benadering wat hiervoor gebruik is, was gebaseer op verskillende stadiums van die bou van 'n ondersteunende multi-kriteria-besluitmodel. Dit het die modellering van die besluitraamwerk deur gebruik te maak van die analitiese hiërargieproses, en die onderneem van 'n onafhanklike gevallestudie, as die basislyn vir die modellering ingesluit.

1 INTRODUCTION

A pallet is a “portable, rigid platform used as a base for assembling, storing, stacking, handling and transporting goods” [1]. The application of pallets covers a wide spectrum of industries, just some of which are the food and beverage, automotive, mining, manufacturing, and chemical and pharmaceuticals sectors.

In the United States of America alone, 1.9 billion pallets are used in various industries [1], [2]. Considering the prominence of pallets, improving their performance should improve operations in most of these industries. This paper aims to provide an understanding of how decision-support tools may help to improve performance by ensuring that the optimum pallet solution is selected.

A critical issue for many in industry is determining which pallet type to use. A decision-support tool is a much-favoured technique to use in order to assess the relative performance of pallets. Various criteria may be used to determine the best pallet for a particular application; however, the effect of the pallet’s material-of-construction has raised a major point of contention in industry [3]–[9], which is the focus of this paper.

More often than not, decision-support algorithms and tools in the pallet industry focus on the management of these returnable transport items within the supply chain [10] rather than on pallet selection. This work aims to break this trend by offering an approach for the development of such a support tool. This approach was used in the development of a private in-house tool, with the data based on a case study for the given use case scenarios. This paper was motivated by the lack of decision methods that understand why a pallet is more successful (suitable) in a given environment. The aim was to create a common approach so that both experts and non-experts could use historical decision information to support the evaluation and selection of the optimal pallet. The contribution of this paper is to be able to formalise an approach to building a material-of-construction (MOC) assessment model for pallets.

2 BACKGROUND

The economic need for cost-saving measures has driven many industries to review their packaging costs, and the pallet is no exception [11]. At present, wooden pallets have the perceived advantage over pallets made with other materials owing to their low cost, versatility, and ease of disposal [11]. However, plastic pallets have increased their market share, primarily because they are durable and recyclable. This growing trend away from wood towards other materials makes it important to optimise pallet selection for a given supply chain or industry.

Decision-support tools in industry normally focus on the management of supply chains, as they help to assess the impact that changes can have on a system prior to their implementation [10]. These support tool strategies can also help to find optimum solutions for pallets as they interact with various kinds of equipment in a specific supply chain network (SCN).

The basis of the multi-criteria decision analysis approach taken here is to model the pallet selection conundrum as a multi-objective optimisation (MOO) problem. The decision to select a particular pallet for an SCN is based on the evaluation of multiple objectives using a set number of criteria.

2.1 Multi-objective optimisation

The generic representation of a MOO problem can be formulated as follows [12]:

$$\Phi(x) = [f_1(x), f_2(x), f_3(x), \ldots, f_m(x)] \longrightarrow \frac{min}{x \in X} \tag{1}$$

where:

- $X \varepsilon R^n$ is a non-empty set of viable decision options
- $x = [x_1, x_2, x_3, \ldots, x_n] \varepsilon X$ is a real n-vector set; and
- $f_i = R^n \rightarrow R$ are the objective functions for the problem

Assumptions:

- All constraints are embedded within each objective function; and
- Constraints are used by means of penalty functions, formed as: $a_j \le f_j(x) \le b_j$.

As can be noted from Equation 1, the objective when solving a MOO problem is to arrive at the optimal solution by finding the extreme value (be it minimum, maximum, or equal) of each of the functions that make up the problem. However, this is a difficult task, and is often unattainable. As a result, the decision problem-solver often seeks a compromise solution that is the best of the possible solutions [13]. This notion is what leads to concepts of Pareto optimality.

2.2 Pareto optimality

Pareto optimality, or a Pareto optimal solution (especially in the context of MOO), can be defined as "finding a solution that maximises the degree of satisfaction and minimises the degree of dissatisfaction of an intuitionistic fuzzy decision" [14]. These forms of solution are the only acceptable types in the realm of MOO, as all other solution types may be improved upon.

The Pareto optimal solution can be mathematically defined as the subset:

$$WP(X) = \{x^p \in X\!:\ such\ that\ there\ does\ not\ exist\ x \in X\ with\ f_i(x) \le\ f_i(x^p), \forall i\ \in 1\!:\!l\,\} \tag{2}$$

This Pareto optimal solution may be further illustrated graphically (Figure 1) for a two-dimensional MOO problem harbouring two objective functions [12]. As illustrated by Abakarov *et al.* [12], the utopia vector Φ^* is the vector that contains the individual global minimums for each of the objective functions.

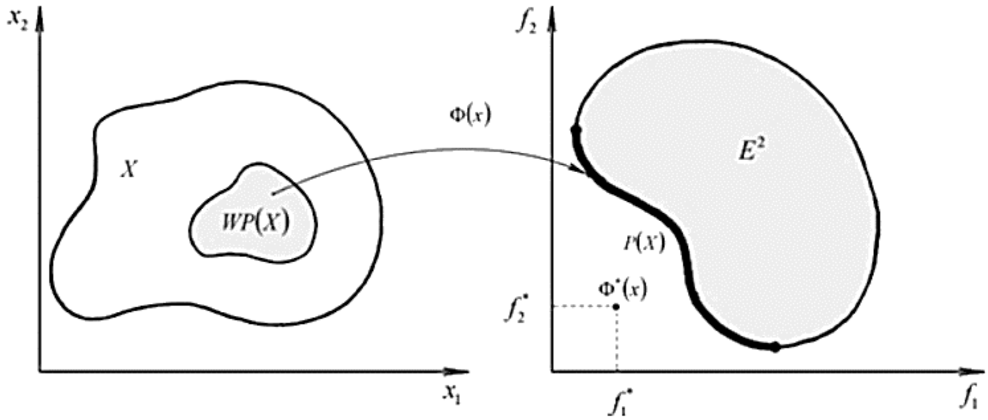

Figure 1: Two-dimensional representation of MOO problem and Pareto optimal solution [12]

In order to find Pareto optimal solutions to MOO problems, a few methods can be used in order to solve these multi-criteria problems. Common to all of them is the notion that most decision-making can be improved by reducing the complexity of the decision through the evaluation of alternatives using a set number of relevant criteria.

Methods such as the analytic hierarchy process (AHP), the analytic network process (ANP), the multi-attribute utility theory (MAUT), the measuring attractiveness by a categorical based evaluation technique (MACBETH), the preference ranking organisation method for enrichment evaluation (PROMETHEE), the technique for order preference by similarity to the ideal solution (TOPSIS), and *elimination et choix traduisant la realité* (ELECTRE) are applied [15]. However, in the context of this work, the focus will be mainly on the tabular method and AHP, which employ a decision matrix and cost benefit analysis (CBA) as the final stage once cost data has been presented.

2.3 Tabular method

The tabular method (TM) established by Sushkov in 1984 is used as a flexible approach to effectively and quickly selecting the best options from a wide range of initial alternatives [12].
The steps that underpin the TM are as follows [16]:

1. Create table/matrix with rows representing the alternatives, and columns relating to the criteria of these alternatives, as indicated by Equation (3);
2. For each given criterion (column), put the set of alternatives in the order of most to least favourable;
3. Delete all non-Pareto-optimal solutions from the table;
4. Impose constraints on the remaining criteria (mainly the worst-case values);
5. Check whether any non-empty sets of solutions (alternatives) satisfy the constraints; and
6. Repeat steps 4 and 5 until a feasible set of solutions is obtained.

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{bmatrix} C_1 & C_1 & \dots & C_n \\ x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_2 \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \tag{3}$$

Tabular method table/matrix, where:

- A_y = Alternative
- C_y = Constraint

- x_{yy} = Value of given criterion

2.4 Analytic hierarchy process

The analytic hierarchy process (AHP) is an effective decision-making approach when dealing with MOO problems. It is a type of multi-criteria decision-making technique that was initially introduced by Saaty [17]. The method simplifies complex decisions by making the process more systematic [18].

This decision-support tool uses a multi-level hierarchical structure that comprises objectives, criteria, sub-criteria, and alternatives [17] (Figure 2). In order to obtain pertinent data to be used in its mathematical approach, the approach uses the measurement of pairwise comparisons and the judgements of experts in order to derive the priority scales used in the analysis [19].

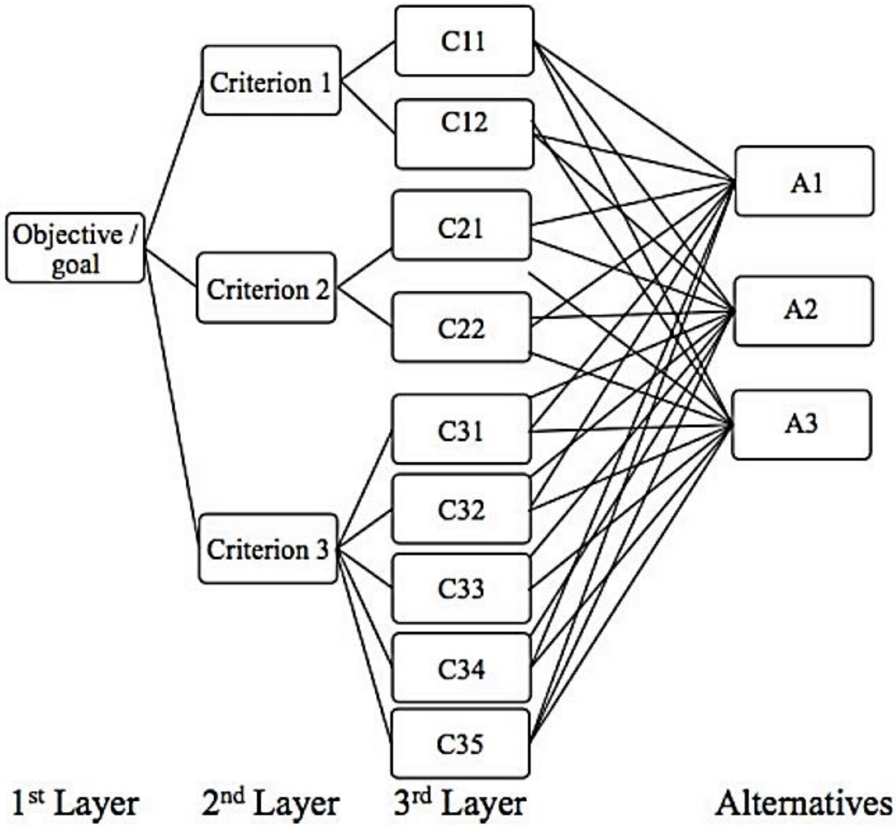

Figure 2: Standard hierarchy architecture of AHP [19]

AHP is a common method used to solve multi-criteria decision-making challenges in various industrial sectors such as supply chain, logistics, and training; it is excellent for assessing strategy and performance, and would be well-suited for application to pallet selection [15].

3 MODEL DEVELOPMENT

There are various 'in-house' studies from pallet manufacturers and service providers that do have some merit; however, some assumptions made in these studies may be biased and not completely transparent [20] (Table 1). The trend seen here shows that wood pallet manufacturers and suppliers see their product as the better option, as do plastic pallet companies, while neutral parties identify the benefits of either, under certain conditions. The lack of independent academic research in this regard creates the opportunity to probe the issues relating to pallet-type selection criteria and to provide reproducible comparisons.

Table 1: Perceptions of wood vs plastic pallets

#	Preferred pallet MOC				
	Wood	Plastic	Depends	Key factor(s)	Reference
1	√			Wood sustainability, low energy requirement	[21]
2			√	Multi-criteria decision	[3]
3		√		Quality, durability, and dependability of plastic	[4]
4			√	Multi-criteria decision	[22]
5			√	Load weight (if >1500 lbs or 680 kg), international shipment	[8]
6	√			Cost, environmental impact	[23]
7			√	Multi-criteria decision	[24]
8		√		Carbon footprint, lifespan	[9]
9			√	Multi-criteria decision	[25]
10		√		Load savings, sustainability	[26]

This approach to developing the tool (incorporating the test case scenario of three different pallets used in a case study) uses varied methods. The first stage in tool formulation is to ensure that the tool outputs only Pareto-optimal solutions. In order to achieve this, the TM may be employed in order to eliminate all non-Pareto solutions or in this case alternatives. However, since in the case of this study, there are only three pallets used as alternatives for a set of decision criteria, each pallet solution would be Pareto optimum and the TM will thus not be used.

The second stage involves the application of a multi-criteria decision making (MCDM) technique. With a vast literature and varied application of its use, the AHP proposed by Saaty was the technique of choice, as it is well-documented and is highly effective [27]. The final stage would be to review and apply the results of any of the techniques or to refine one of the steps in the decision-making process. In this case, seeing that stage one is catered for, the sections that follow will elaborate on the AHP process and its implementation.

3.1 Analytic hierarchy process — procedure

AHP applications use four steps to come to a decision about a given set of alternatives. The steps below are elaborated on in the context of this study.

The steps involved are [27]:

STEP 1: Structuring of the decision problem
STEP 2: Making pair-wise comparisons and obtaining the judgemental matrix
STEP 3: Computing the local weights and the consistency of comparisons
STEP 4: Aggregation of local weights

The first step involves formulating the decision problem into a hierarchical model, which normally contains levels relating to the goal, criteria (with possible multiple sub-criteria), and alternatives [27]. In this tool formulation, a pallet selection framework is presented (Figure 3) containing the list of suitable decision criteria.

The second step incorporates the use of pairwise comparisons, which are the basis of the AHP [28]. Elements in a particular level are compared, using the fundamental comparison scale in Table 2 on a pairwise basis, with the next level up in the hierarchy [27]. The comparison requires the decision-maker's judgement in order to select an intensity of relative importance; or, in the case of this study, ratings are made in relation to the results for each criterion (as well as the author's judgements based on the experience gained while conducting the study). These ratings form the foundation of a judgemental matrix that is governed by the following rules for each entry a_{ij}:

1. $a_{ij} > 0$
2. $a_{ij} = 1/ a_{ji}$
3. $a_{ii} = 1$ for all i

In order to compute the relative importance of an alternative in a judgemental matrix in relation to the criteria being evaluated, Saaty proposed the calculation of the right principal eigenvector of the matrix to calculate the normalised value of each element.

Table 2: Fundamental comparison scale used by Saaty [29]

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured, and its dominance is demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When a compromise is needed
Reciprocals	If activity 'i' has one of the above non-zero numbers assigned to it when compared with activity 'j', then activity 'j' has the reciprocal value when compared with 'i '.	

Given the nature of the pairwise comparisons indicated earlier, it is possible that comparisons will prove to be inconsistent. The AHP technique only caters for this by introducing a consistency ratio (CR) for which, if the value is less than 0.1, the pairwise comparisons are said to be adequate. The CR is obtained by dividing the consistency index (CI) by the random consistency index (RCI), which is provided in Table 3 [17] (Equation 4). This process is, in essence, what step 3 entails.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{4}$$

where:

- n = number of elements in the row of the matrix
- λ_{max}= maximum eigenvalue associated with previously calculated eigenvector

Table 3: RCI values for different values of n [17]

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The final step is an aggregation of each of the weights at each level of the hierarchy using an arithmetic aggregation rule for each of the criteria and alternatives. Thus, for a problem with M alternatives and N criteria [17], the following equation would apply:

$$A^{i}_{AHP} = \sum_{j=1}^{N} a_{ij} \times w_j \; for \; i = 1,2,3,\ldots,M \tag{5}$$

where:

- A = decision matrix of final priorities
- a_{ij} = judgement matrix of criteria being compared
- w_j = local weights of the next level up

3.2 Identification of decision criteria

Below are some definitions of the criteria and sub-criteria that are used in formulating the decision framework (Figure 3). Each criterion is briefly described for how it relates to pallet selection, as well as comparative findings found in the literature in relation to wood and plastic pallets. In this tool, the data from this study (as formulated by the author) was used and, where none existed, findings from the literature were used to supplement the given data.

3.2.1 Operational comparison

Roughness/smoothness and rack ability
The ability to use a pallet easily for racking in the distribution environment:

- Plastic pallets are more susceptible to slipping than their wooden counterparts, owing to the smooth nature of the polymer surface, which can pose a safety concern in racking environments [30].

Life cycle/durability — expected useful life
The useful lifespan of a pallet and its durability under different use cases:

- The projected lifespan of a plastic pallet is around 10 years [30].
- Wooden pallets can have a 3—5 year lifespan [24], although this is difficult to assess with repairs.

Operating conditions
The operating conditions that are best suited to pallet type, and outlines of which conditions might have adverse effects:

- Wood is known to be sensitive to water, as it can warp when exposed, and potentially rots and grows fungi.
- Plastic becomes brittle when exposed to sub-zero conditions and so it might not be suitable for use in very cold temperatures.

Risks — pallet flammability, occupational hazards from handling pallets
All types of equipment come with associated risks. This criterion emphasises the risks associated with a particular pallet MOC.

- Smooth surfaces make them slippery, which can prove to be an operational risk [30].
- Broken elements from wood can pose a serious safety risk, as protruding nails and sharp elements can cause injury.

Consistency — variable weight with water contact, humidity, or any other factors
Pallet consistency is important in predicting behaviour and expected performance. This criterion caters for this variable.

- Wood: Because they are made with different elements and material properties, wood pallets are susceptible to weight inconsistencies, and may yield unreliable performance [31].
- Plastic: Chemical properties make these pallets more durable and more resistant to weather elements.

3.2.2 Environmental comparison

Recyclability and disposal
The associated impacts of disposal and the ability to recycle a product are key decision factors, and this criterion caters for this.

- Wood, being 100% biodegradable, can be landfilled; however, other end-of-life (EOL) options can be used, such as mulch and animal bedding [5], [32]. Waste-to-energy technologies are also options for recovering energy from waste wood pallets [33].
- Plastic is non-biodegradable and has a long half-life prior to its initial decomposition. Landfilling is not a sustainable option, and other options, such as recycling, need to be adopted [31], [32].
- Plastic pallets may be made from recycled material, and may be recycled at EOL [32]. This promotes a circular plastic economy that reduces landfilling and waste material.

Regulations and hygiene — infections, parasites, mould, etc. and repercussions
Most products are regulated according to some standard; and this can impact on the operation or adoption of a particular pallet type. This criterion explores this potential concern.

- Regulations such as the ISPM 15 require exported wood pallets to be heat-treated. This is done to eliminate the transfer of pests between countries.
- The heat treatment of pallets is energy-intensive, and thus can increase CO2 emission levels.

Manufacturing — source of materials used for pallet manufacture (local/imported)
The impact of manufacturing activities associated with the manufacture of a pallet of a type of MOC may have an impact on costs, pollution and overall sustainability.

- Plastic pallet manufacturing is highly energy-intensive, using up to five times the energy consumption in manufacturing wood pallets; thus it produces more CO2 emissions [32].
- Forest depletion is a major environmental concern for pallet manufacturing from wood [31]; however, major pallet manufacturers are actively engaged in reforestation.

Sustainability — sustainable benefits/shortfalls of the various pallet types
The requirements for assessing a sustainable pallet type and how some may fare against others:

- In order to quantify the sustainability of a given pallet, a full life cycle analysis of the specific pallet, from cradle to grave, needs to be carried out following ISO14040 guidelines [32].
- Pallets from wood are completely biodegradable. Plastic, on the other hand, is non-biodegradable and must be recycled [30].

3.2.3 Economic comparison

Cost — detailed cost breakdown by element
Costs are normally the driving force in many decisions in industry. This criterion caters for this, although a cost benefit analysis can also be carried out in isolation.

- Wood pallets for export require heat treatment, which requires a larger energy input for kiln operation, and thus a higher associated energy cost.
- Mechanical failure, such as the broken elements and protruding nails of wood pallets, can lead to damaged goods, injuries, customers' returns, legal claims, or delays in moving material, any of which ultimately decrease the total efficiency and increase the operating costs [34].
- Exporting wooden pallets offers a cheaper alternative to plastic ones, as wooden pallets are rarely returned, if ever [22], [24].
- As fuel consumption is the most significant energy cost in unit load transportation, a reduction in either size or volume of the unit load could improve the operational efficiency of goods transportation in the supply chain.

Repair/maintenance — ability to clean, condition, and repair pallets, and the cost of repair and maintenance
Maintenance and repair costs may have a significant impact on the economics of a decision about pallet selection.

- Wooden pallets are repairable; however, a cost is associated with transporting damaged pallets that in addition to costs for repairing facilities, cost of elements, fasteners, and labour.

Pallet footprints
This criterion defines and caters for the availability of sizes, specifications, pallet weight, and other similar factors associated with a given pallet MOC.

- With more than 80% of freight moved by road in South Africa [35], consideration needs to be given to reducing the load weight of pallets. Lighter pallets reduce the load on trucks, thus reducing the fuel requirements (and costs); and thus CO_2 emissions are reduced as well [24], [32].
- Plastic pallets can be as much as 30% to 50 % lighter than wooden pallets. On this basis, plastic pallets could reduce a trailer load's weight by between 500 and 2000 lbs (230–900 kg) [5], [32].

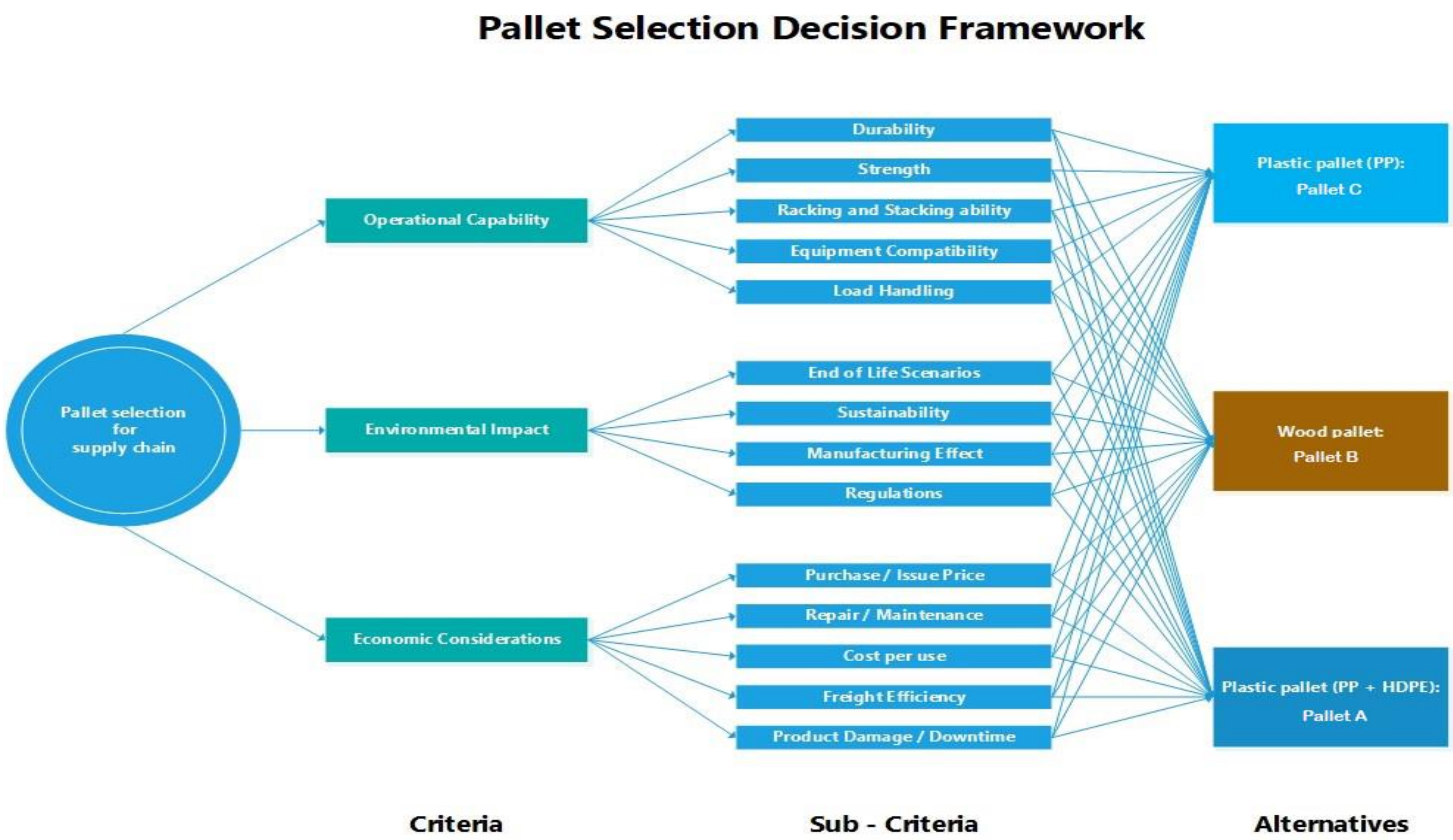

Figure 3: Pallet selection framework

4 RESULTS

As stated, the objective of this study is to assess pallet MOC options and to select the one that would be best for a particular SCN. For this purpose, a solution using a perishables supply chain case study is formulated. The procedure is then followed for different supply chains and for each criterion and sub-criterion. For the purpose of illustration, only the operational capability criterion (Figure 3) will be explored.

Three pallets are used as alternatives: Pallet B wood pallet, Pallet A plastic pallet (PP+HDPE), and Pallet C plastic pallet (PP), as indicated in the preceding selection framework (Figure 3). They are referred to as alternatives, and each is denoted by the letter A and a subscript indicating the MOC (A_{WOOD}, $A_{PP+HDPE}$, and A_{PP} respectively where PP indicates polypropylene, and HDPE refers to High-density polyethylene). Similarly, each criterion and sub-criterion is denoted by the letter C and a subscript that defines the element (e.g., C_{DUR} for the durability sub-criterion) or a suitable shorthand.

4.1 Solution pathway

Each of the alternatives are pairwise compared with each sub-criterion using the procedure outlined in Section 3.3.1 and the framework in Figure 3. The results from a case study are used as the foundation for the pairwise comparisons. To illustrate this, the first sub-criterion by which to assess the three alternatives is durability (C_{DUR}).

From the reference case study, a determination of which pallet type was the best performer can be made. Pallet C plastic (A_{PP}) was the best performer in the durability segment of the case study, scoring 5/5, with Pallet A plastic ($A_{PP+HDPE}$) and Pallet B wood (A_{WOOD}) receiving scores of 4/5 and 3/5 respectively. These scores were obtained during field observations of their performance while conducting the case study. The pallets were rated out of 5 on their performance in line with what was expected on the site. In respect of the judgement matrix for C_{DUR}, the fundamentals scale from Table 2 is used to rank each pair, based on the case study results. In respect of durability, the Pallet C plastic (A_{PP}) pallet was the best overall performer and was much better than Pallet B wood (A_{WOOD}) and Pallet A plastic ($A_{PP+HDPE}$); it received pairwise ratings of 9 and 7 against each respectively. Pallet A plastic pallet was only marginally more durable than Pallet B wood pallet, and as such it scored 3 on this comparative scale. This ranking procedure is used to formulate the judgement matrix (Table 4).

Once the matrix has been computed, the right principal eigenvector and the associated eigenvalue are calculated, following the procedure, to obtain the priority vector and the supplementary CI and CR values.

Table 4: Comparison of alternatives in relation to sub-criterion C_{DUR}

C_{DUR}: **Durability**	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	Right principal eigenvector	**Priority vector**
A_{WOOD}	1	1/3	1/9	0.084	**0.0658**
$A_{PP+HDPE}$	3	1	1/7	0.189	**0.1488**
A_{PP}	9	7	1	1	**0.7854**

λ_{max} = 3.0803, CI = 0.0402, and CR = 0.0692

The output gives a CR value of 0.0692, which is less than 0.1, and so confirms that the comparisons were adequate and within reason. The same procedure is then followed for each of the remaining sub-criteria. To illustrate further how the AHP process works, the next matrix explores in depth how comparisons are made. The strength (C_{STR}) sub-criterion (Table 5) was slightly different from the initial matrix, in that it is based predominantly on the pallet testing done as preliminary work for the case study. This is because data on strength cannot be obtained in the distribution environment. Using the stacking and racking deflection results, we can compute some pairwise comparisons for the strength sub-criterion.

In the matrix, the A_{WOOD} *vs* A_{WOOD} comparison is given a value of 1 (for a_{11} in the matrix), as they are of equal importance (as in Table 2); for $A_{PP+HDPE}$ *vs* A_{WOOD} a value of 2 is assigned for a_{21} because Pallet A, although the best performer in the tests, has only a slight advantage in this regard. Following the rules of the judgement matrix, a_{12} is subsequently assigned the value of $1/a_{21}$ — i.e., 1/2. Similarly, when comparing the results of A_{PP} *vs* A_{WOOD}, a value of 1/3 is assigned to a_{31}, as wood is marginally better, considering both tests, than the polypropylene pallet (A_{PP}). This procedure is adhered to for all the other criteria (See Tables 5 and 6).

Table 5: Comparison of alternatives in relation to sub-criterion C_{STR}

C_{STR}: Strength	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	Right principal eigenvector	Priority vector
A_{WOOD}	1	1/2	3	2.621	**0.3196**
$A_{PP+HDPE}$	2	1	4	4.579	**0.5584**
A_{PP}	1/3	1/4	1	1	**0.1220**

λ_{max} = 3.01829, CI = 0.00915 and CR = 0.0157

Similarly, the sub-criterion for $C_{R\&S}$ was based on the tests performed in the case study.

Table 6: Comparison of alternatives in relation to sub-criterion $C_{R\&S}$

$C_{R\&S}$: racking &stacking	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	Right principal eigenvector	Priority vector
A_{WOOD}	1	1/3	1	0.874	**0.2098**
$A_{PP+HDPE}$	3	1	2	2.289	**0.5499**
A_{PP}	1	1/2	1	1	**0.2402**

λ_{max} = 3.01829, CI = 0.009145 and CR = 0.01577

According to the results obtained in the case study, all of the pallets performed equally well in the perishables supply chain, and so this sub-criterion was left out of the calculations.

The load sub-criterion was based predominantly on the quoted load-carrying capacities of the pallet manufacturers.

Table 7: Comparison of alternatives in relation to sub-criterion C_{LOAD}

C_{LOAD}: Load handling	A_{WOOD}	$A_{PP+HDPE}$	A_{PP}	Right principal eigenvector	Priority vector
A_{WOOD}	1	1/4	3	2.241	**0.2255**
$A_{PP+HDPE}$	4	1	5	6.694	**0.6738**
A_{PP}	1/3	1/5	1	1	**0.1007**

λ_{max} = 3.08577, CI = 0.042885 and CR = 0.07394

Once all of the alternatives (pallets) have been assessed in relation to the sub-criteria, the sub-criteria need to be given local relative weights, using the same procedure as above, but in relation to the overall criterion — i.e., operational capability.

Table 8 gives this comparison. Unlike with the sub-criteria, the pairwise comparison is based entirely on the decision-maker's experience in the perishables SCN. In this case, the author uses prior knowledge obtained during the case study to rank each item. As an indication of the rationale, the sub-criterion of durability (C_{DUR}) is ranked the highest of all of the sub-criteria, as the SCN is fast-paced, and pallets spend little time in racking and stacking configurations.

Table 8: Comparison of sub-criteria in relation to the parent criterion C_{OPER}

C_{OPER}: Operational capability	C_{DUR}	C_{STR}	$C_{R\&S}$	C_{LOAD}	Right principal eigenvector	Priority vector
C_{DUR}	1	5	8	9	15.605	**0.6713**
C_{STR}	1/5	1	2	5	4.125	**0.1775**
$C_{R\&S}$	1/8	1/2	1	4	2.514	**0.1082**
C_{LOAD}	1/9	1/5	1/4	1	1	**0.0430**

λ_{max} = 4.18741, CI = 0.06247 and CR = 0.06941

This final resulting priority vector is multiplied by the priority vectors obtained from the judgement matrices of each of the sub-criteria in order to obtain a final weight for each alternative on the basis of its operational capability; each row in the matrix product below relates to a particular alternative (A_{WOOD}, $A_{PP+HDPE}$, and A_{PP} respectively):

$$\begin{pmatrix} 0.0658 & 0.3196 & 0.2098 & 0.2255 \\ 0.1488 & 0.5584 & 0.5499 & 0.6738 \\ 0.7854 & 0.1220 & 0.2402 & 0.1007 \end{pmatrix} \begin{pmatrix} 0.6713 \\ 0.1775 \\ 0.1082 \\ 0.0430 \end{pmatrix} = \begin{pmatrix} 0.133 \\ 0.287 \\ 0.579 \end{pmatrix}$$

From the results of this process, it is noted that A_{PP} was the overall best performer in respect of operational capability, with an overall weight of 0.579. This is based on the selection criteria and the associated weights according to perceived significance and relevance in the perishables supply chain. These results can help a decision-maker when having to select a pallet type from among the three for the conditions set out in the case study.

5 CONCLUSION

In most cases, the decision between one pallet's material-of-construction and that of the next is complex, as a multitude of variables need to be considered. Thus, the approach of this paper was to frame the problem not as a comparison to see which MOC was best, but rather as an application of MCDA methods in order to formulate a solution. Given the test case scenario with the pallets, the polypropylene-based plastic pallet, A_{PP}, was found to be the best-performing pallet from among the test specimens for the perishables supply chain. This outcome can be used to quantify and justify the use of that pallet type in a supply chain because it matches the parameters observed in the perishables supply chain. This method can also be expanded to include various other supply chains, pallet types, and specifications.

In addition, the proposed arithmetic approach has been applied in a proprietary in-house software-based MCDA tool for pallet selection for a local company and has shown to be useful in pallet selection. However, widespread adoption beyond the case study is yet to be realised. This tool formulation procedure may be used in the development of similar specific MCDA tools for application in other fields or scenarios. The main benefits of this approach and of such a tool are that it allows the user to pick a pallet solution objectively, given the plethora of factors that need to be considered and, in doing so, to allow for supply chain optimisation.

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