Evaluation of the Particle Boards for the Construction Projects: A Hybrid MCDM Approach

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Abstract

Particleboard (PB) is an essential engineered product, which is often used as a replacement for wood, thus playing a significant role to reduce deforestation and improving environmental sustainability. Proper selection of PB is important to make sure that the chosen product has the required durability and sustainability and thus can maintain the quality of the construction work. This study proposes a Multi-Criteria Decision-Making (MCDM)approach, to evaluate the selection criteria of PB to aid the decision-makers of the civil construction projects. In this approach, the existing evaluation criteria have been categorized into four criteria- Physical Properties, Mechanical Properties, Chemical Properties, Health, and Environmental Impact. Then a Best Worst Method (BWM) has been used to determine the criteria and sub-criteria weights to evaluate the PBs. After that, a Weighted Product Model (WPM) has been applied to generate the final ranking of the products to aid the decision-makers to select the right product. The study finds Emission Level, Moisture Content, and Toxicity as the most weighted evaluation criteria to select a PB. For this study, the required expert feedback has been collected from the supervisors and managers of different construction firms in Bangladesh. The obtained results are expected to benefit the managers, supervisors, and other decision-makers of the construction projects to select the right product for their construction projects to maintain their quality and reputation.

Keywords
Particle Board, Multi-Criteria Decision Making, Best Worst Method and Weighted Product Model.

1. Introduction
PB is mainly manufactured from chips (wood, jute stick, or other waste fibers) with adhesives bonding and pressing at a high temperature (Owodunni et al., 2020). Utilizing various waste fiber for PB manufacturing is the primary benefit of this product, which reduce the demand for natural wood for construction work, furniture, door, and other home appliances. Besides this, PB is more economical than natural wooden products (Bayram, 2020). For these, the world market share of PB is increasing every year. In 2020, the global market of PB was US$ 16830 million, which is expected to be US$ 21410 million by the end of 2027 (360 Research Reports, 2021).

There are several works in recent literature that have depicted various physical, mechanical, and chemical characteristics of PB and some other similar wood-based products. For example, effect of heat treatment on physical and mechanical properties have been evaluated by applying MCDM techniques (Kaymakci and Bayram, 2021), trade-economic contribution of forest products have been evaluated using MCDM method (Bayram, 2020), surface layer properties of PB have been experimented by applying a new filler material (Ozyhar, 2020), relation between releasing formaldehyde, moisture content of the PB, environmental impact, and emission grading has been discussed and reviewed (Owodunni et al., 2020; Hemmilä, 2019; Marutzky, 2018), an MCDM technique, Analytical Hierarchy Process (AHP), has been applied to find the most important types of PBs to export from Turkey (Bayram et al. 2018), correlation between different mechanical properties of PB has been ascertained from empirical values (Kevin et al. 2018), PB has been produced and characterized by using different waste material at different percentage combination (Hassan and Awopetu, 2018; Harshavardhan and Muruganandam, 2017), and so on.

Health, the environmental and economic impact of PB produced from different combinations of raw materials and adhesives have also been discussed in some recent studies (Zhang et al., 2018; Hemmilä, 2019). However, no research has been conducted yet to evaluate the selection criteria through the MCDM approach to select a PB from multiple brands or alternatives. This can be considered a research gap, which is worth exploring.

Though all the evaluation criteria are important to produce the best PB, each of them does not carry the same weight for the selection of the proper PB product by construction project managers or supervisors. Previous studies have determined the mechanical, physical, chemical, environmental, and other properties of PB using various theoretical, mathematical, and empirical methods. However, none have determined the weights of different objective and subjective evaluation criteria of PB and based on those weights, made the final ranking of the PB products. Considering this gap in the literature, this study aims to figure out the weights of the evaluation criteria of PB by BWM and then rank the candidate products by WPM, based on weights determined by BWM.

BWM is a relatively newer, simpler, and more consistent technique, compared to AHP and other pairwise comparison-matrix-based MCDM methods, which are commonly used to find evaluation criteria weights (Rezaei, 2015; Rezaei, 2016). WPM is another efficient MCDM technique that can be used for decision-making from multiple alternatives when the weights of the evaluation criteria are given (Tofallis, 2014). This study aims to utilize both BWM and WPM in a combined or hybrid approach. At first, evaluation criteria of PB extracted from different existing works of literature and expert feedback have been categorized, and then evaluated and weighted with BWM, using the responses from experts. The weights obtained from BWM then have been applied to evaluate different PB products by using WPM, to establish a selection framework. In this mixed-method research, PB has been selected both by the laboratory tests and subjective evaluation from the experts. The laboratory test result has been carried out for the objective evaluation criteria, and experts' feedback has been used for the subjective evaluation criteria. The proposed study is expected to help the managers of different construction projects or furniture manufacturing industries to select the best PB product to suit the need of their construction project or furniture manufacturing.

This research aims to contribute to the literature by addressing the following specific objectives:

a) To identify and enlist the significant evaluation criteria and sub-criteria of PB
b) To find the weights of the evaluation criteria and sub-criteria by applying BWM
c) To generate a PB selection framework by applying WPM

The rest of the paper is presented in the following sections: Section 2 presents a literature review and identifies the evaluation criteria of PB. Section 3 discusses the relevant research methodologies and calculations. Section 4 presents the obtained results and discussions. Section 5 discusses the managerial implications of the research. Finally, Section 6 concludes the paper and discusses some future research directions.

2. Literature Review

Evaluation criteria of PB can be classified broadly as physical properties, mechanical properties, chemical properties, health, and environmental impact (Kibria, 2012, Rowell, 2012). Different heat treatment parameters can bring different results in various physical and mechanical properties of PB and similar types of products. Evaluation of such impact of heat treatment parameters on poplar wood has been conducted using MCDM techniques by Kaymakci and Bayram (2021). They only focused on physical and mechanical properties; other criteria were not discussed. Moreover, that study did not focus on determining the weights of the evaluation criteria of PB, which differentiates it clearly from this current work. The contribution of PB and other forest products to the economy and export of a country has been determined by MCDM methods in some recent works (Bayram 2020, Bayram et al. 2018). Those works tried to evaluate PB and comparable products based on their contributions to the economy and export. However, they did not attempt to evaluate the selection criteria of PB.

Most of the recent studies on PB have been conducted to depict various technical innovations and findings related to manufacturing. For instance, Ozyhar (2020) explored the ways mineral filler in the surface layer affects the mechanical properties of a three-layer PB, along with empirical data. Changes in mechanical, physical, and environmental properties due to the use of various adhesives have also been reviewed and discussed with statistical presentation (Mantanis et al. 2018; Owodunni et al. 2020). Hassan and Awopetu (2018) studied the characteristics of PB manufactured from varied materials and compared them with empirical test results. The physical and mechanical properties of PB manufactured from varied materials have been explored, reviewed, and compared in some papers with theoretical and empirical approaches (Kibria, 2012; Muruganandam et al. 2016, Kevin et al. 2018). Environmental impacts of PB due to various emission levels as well as the way of producing environment-friendly PB have been presented by various researchers (Zhang et al., 2018; Hemmilä, 2019; Razinkov et al., 2019). However, none of the previous research proposed any analytical decision-making method for the selection of PB based on different significant evaluation criteria, which is the prime objective of this research.

Two MCDM techniques have been utilized in this research- BWM, and WPM. BWM has been utilized in various recent decision-making works like evaluation of renewable energy resources (Mousavi-Nasab and Sotoudeh-Anvari, 2020), selection of the best location for a specific purpose (Hashemi and Azari, 2021), performance evaluation of a company (Dwivedi et al., 2021), robot selection for an industrial purpose (Ali and Rashid, 2021), prioritization of the barriers behind sustainable manufacturing (Malek and Desai, 2019), etc. WPM has also been used for diverse selection related decision-making problems like daily life product selection (Goswami et al. 2020), house selection with multiple criteria (Supriyono and Sari, 2018), best employee selection during the recruitment process (Susanto and Andriana, 2019), best dealer selection for a specific product (Alexander and Ameliza 2021) and so on. However, no previous research has used a hybrid BWM-WPM method so far to evaluate any civil construction material, which justifies the rationale of the proposed study.

Based on the review of the existing literature and suggestions from the experts, the most significant evaluation criteria used in the PB industry have been listed and categorized in criteria and sub-criteria. Details description and source of the evaluation criteria has shown in Table 1.

Table 1. Existing evaluation criteria of PB

Criteria	**Source**	**Sub-criteria**	**Description**
Physical Properties (P)	(Kevin et al., 2018; Muruganandam et al., 2016; Kibria, 2012; Expert feedback)	Thickness (P1)	The standard thickness for a PB is measured in mm (Objective criterion). Proper thickness of PB is important for the structural accuracy of the finished products.
		Density (P2)	The standard density for a PB is measured in kg/m^3 (Objective criterion). Proper density of PB can assure strength, thermal resistance, sound resistance, and so on.
		Swelling (P3)	Swelling is measured in % of thickness increase after keeping PB in contact with water for a certain period (Objective criterion). It is important to measure the water-resistance quality of PB.
		Color (P4)	Color depends on materials and machine-related issues (Subjective criterion). It can be helpful to decide the surface smoothness and gluing performance of PB.

Mechanical Properties (M)	(Muruganandam et al., 2016; Ozyhar, 2020; Hassan and Awopetu, 2018; Expert feedback)	Bending Strength (M1)	BS can be described as a function of resisting strength when a PB faces bending force. It is also measured as Modulus of Rupture (MOR), the unit of measurement is N/mm^2 (Objective criterion).
		Modulus of Elasticity (M2)	MOE is the measurement of the resisting strength of a PB before permanent deformation. It is measured in N/mm^2 (Objective criterion).
		Screw Withdrawal Strength (M3)	Screw Withdrawal Strength (SWS) is a criterion of material strength measured in N, by pulling a penetrated screw from a PB (Objective criterion). It can measure the capability of PB to be joined together using a mechanical screw for building structures.
		Surface Soundness (M4)	Surface Soundness (SS) is the strength of the surface layer of a PB, which is important for the durability of the finished products. It is measured in N/mm^2 (Objective criterion).
		Tensile Strength (M5)	Tensile Strength (TS) describes the Internal Bond (IB) strength of a PB. It is measured in N/mm^2 (Objective criterion). The bonding strength between the core layer and surface layer of PB can be determined by TS.
Chemical Properties (C)	(Hassan and Awopetu, 2018; Zhang et al., 2018; Expert feedback)	Moisture Content (C1)	The amount of aqueous or liquid content in PB can largely affect other properties, which is measured in % (Objective criterion)
		Base Material Property (C2)	The base material is the chip forming material of PB (Subjective criterion). Property of the base material can impact the chemical property and quality of the final product.
		Binding Material Property (C3)	Binding material is the adhesive material of a PB (Subjective criterion). The property of the binding material can impact the chemical property and quality of the final product.
Health and Environmental Impact (H)	(Zhang et al., 2018; Hemmilä, 2019; Expert feedback)	Emission level (H1)	Based on formaldehyde emission amount, there are E0, E1, and E2 level, which is measured in $mg/m^2.hr$. Emission level shows the impact of PB on health and the environment. (Objective criterion)
		Toxicity (H2)	Anti-termite and Anti-fungal chemicals used in producing PB can be detected by this criterion (Subjective criterion). There is an international standard to control the number of such chemicals used in production.
		Odor (H3)	Different raw materials for production may cause odor (Subjective criterion). Its limit depends on users' acceptability.

3. Methodology and Calculations

This study focuses to develop a simplified and functional framework for the selection of PB for construction projects by evaluating based on its evaluation criteria. For this purpose, a methodology has been designed, which is explained below in 5 steps.

Step 1. A group of Industrial experts has to be selected to get feedback for evaluation.
Step 2. Sort out the most significant evaluation criteria for PB from existing literature, expert opinion, and international standards.
Step 3. The selected evaluation criteria need to be weighted by BWM based on expert opinion.
Step 4. PB from different brands should be assessed in the laboratory following proper standards for the numerically measurable evaluation criteria. Immeasurable criteria should be evaluated on a linguistic scale by experts.
Step 5. Evaluation scores for each of the PBs have to be assessed by WPM to select a PB from multiple alternatives.

Experts are needed to opine on enlisting and categorizing evaluation criteria and evaluation by the BWM-WPM approach. A group of 9 experts has been separately surveyed online via Google forms to get their feedback and response at different steps. Table 2 is depicting a brief profile of the participating experts in this study.

Table 2: Participating experts' profile

Construction Project Experts (N=9)			
Managers and Supervisors of construction firms (N=9)	**Experience**	**N**	**Percentage**
	From 5 up to 10 years	3	33%
	From 10 up to 15 years	4	44%
	More than 15 years	2	23%

3.1 BWM

A simple questionnaire-based form needs to be filled out by the experts to apply BWM for figuring out the weights of the evaluation criteria. Details procedure (Rezaei, 2015; Rezaei, 2016) of BWM are as follows:

Step 1. The best criterion (most important criterion) and the worst criterion (the least important criterion) are nominated by each of the experts.

Step 2. The significance of the most important criterion over all other criteria is decided on a scale of 1 to 9 rated by the experts. Here, 1 is for 'equal importance' and 9 is for 'extremely high' importance. Mathematical presentation of 'Best to Others' relation for the Mth expert is as Equation (1).

$$X_B^M = \left(x_{b1}^m, x_{b2}^m, \dots, x_{bj}^m\right) \tag{1}$$

Where, x_{bj}^m shows the importance of the best (B) criterion compared to any other criterion J.

Step 3. Following a similar procedure to Step 2, the 'Others to Worst' relation is decided where the importance of all other criteria over the worst criterion is figured out. Mathematically this relation is as Equation (2) for the Mth expert.

$$X_W^M = \left(x_{1w}^m, x_{2w}^m, \dots, x_{jw}^m\right) \tag{2}$$

Where, x_{jw}^m shows the importance of the criterion J compared to the 'worst' criterion (W).

Step 4. Optimal weights of the criteria are found by solving a linear programming problem stated below-

$$Min\ \xi^L$$

Subject to,

$$\left|W_B^M - x_{bj}^m W_J^M\right| \le \xi^L \quad \text{for all } j \tag{3}$$

$$\left|W_J^M - x_{jw}^m W_W^M\right| \le \xi^L \quad \text{for all } j \tag{4}$$

$$\sum_j W_J^M = 1 \tag{5}$$

$$W_J^M \ge 0 \text{ for all } j \tag{6}$$

Here, according to the Mth expert, W_B^M is the weight of the most important criterion; W_W^M is the weight of the least important criterion; W_J^M is the weight of any J criterion

Weights $(W_1^M, W_2^M, \dots, W_J^M)$ are calculated by solving Equation (3) to (6) minimizing the value of ξ^L. The nearer the value of ξ^{L*} (Ksi*) is to 0, the more consistent the weights are.

Step 5. Weights obtained from all the experts are aggregated with a geometric mean (GM) with Equation (7).

$$\text{GM} = \bar{W_j} = \sqrt[M]{W_J^1 W_J^2 \cdots W_J^M} \tag{7}$$

Step 6. Normalization is done to the aggregated weights with Equation (8), to find the final value of the weights for all the criteria.

$$W_C = \frac{\bar{W_j}}{\Sigma_{J=1}^J \bar{W_j}} \tag{8}$$

Step 7. Similar procedures need to repeat for finding the weights of the sub-criteria for each of the criteria. Finally, the Global weights of the sub-criterion are calculated by multiplying by the weights of the respective criterion, which has been shown in equation (9).

$$W_G = W_C \times W_S \tag{9}$$

Here, W_G= Global Weights of Sub-criteria; W_C= Aggregated Weights of Criteria; W_S= Aggregated Weights of Sub-criteria.

3.2 Quality Checking of PB from Multiple Brands

Subjective criteria (see Table 1) of the PBs can be evaluated by expert feedback. For this, a questionnaire-based response has been collected by using a 5-point Likert scale as shown in Table 3.

Table 3. A 5-point Likert scale to evaluate the subjective evaluation criteria of PB

Linguistic Variable	Numerical Value
Very Low	1
Low	2
Medium	3
High	4
Very High	5

The objective criteria of the PBs are needed to be evaluated in the laboratory following proper standard guidelines. International standard of the objective criteria (see Table 1) for a jute-based PB of 18-mm thickness can be found in Table 2A in Appendix A. (Standard values will differ with the change of thickness and be different for the various base and binding materials. This study considers only a single type of PB from multiple brands as an example to present the selection process).

3.3 WPM

A decision matrix for applying WPM is formed with the aggregated responses from the experts for the subjective criteria and the empirical value for the objective criteria. The procedure (Tofallis, 2014) can be written as below:

Step 1. Beneficial and Non-beneficial criteria are needed to be detected. The criterion which is desired to be larger is beneficial, and the criterion which is desired to be smaller is non-beneficial.

Step 2. Normalization of the decision-matrix is computed by below mentioned two equations, where Equation (10) is for beneficial criteria and Equation (11) is for non-beneficial criteria.

$$\bar{Z}_{ij} = \frac{Z_{ij}}{Z_j^{\max}} \tag{10}$$

$$\bar{Z}_{ij} = \frac{Z_j^{\min}}{Z_{ij}} \tag{11}$$

Step 3. Weighted normalized decision-matrix can be derived by Equation (12)

$$A_i^{WPM} = \prod_{j=1}^{n} Z_{ij}^{w_i} \tag{12}$$

Step 4. Elements of each of the rows of the weighted normalized decision matrix are multiplied to get the final evaluation score. Selection of the preferred product is completed by considering descending order of the scores.

3.4 Calculations

Weights of the evaluation criteria for this study have been calculated by using the feedback from 9 experts (can be denoted as Ex to Ex-9) collected through the survey questionnaire. A sample of the feedback collected from an expert can be found in Table 1A in Appendix A. Result of the calculated weights of the criteria can be found in Table 4.

Table 4. Calculated weights of the criteria

Criteria Code	Ex-1	Ex-2	Ex-3	Ex-4	Ex-5	Ex-6	Ex-7	Ex-8	Ex-9	Aggregated Weights	Normalized Weights
P	0.129	0.118	0.154	0.133	0.147	0.128	0.108	0.136	0.092	0.126	**0.132**
M	0.226	0.265	0.385	0.200	0.176	0.447	0.243	0.477	0.254	0.280	**0.293**
C	0.226	0.176	0.231	0.333	0.412	0.170	0.243	0.182	0.169	0.227	**0.237**
H	0.419	0.441	0.231	0.333	0.265	0.255	0.405	0.205	0.485	0.323	**0.338**
Ksi*	0.032	0.088	0.077	0.067	0.118	0.064	0.081	0.068	0.023		

Based on the experts' evaluation, the calculated weights of the sub-criteria have also been determined, which can be found in Table 3A of Appendix A. Normalized weight for each of the sub-criteria is the weight for that sub-criterion in the respective cluster of criteria. These weights need to be globalized based on the criteria weights which have been shown in Table 4. Calculated globalized weights of the sub-criteria which have been utilized in WPM can be found in Table 5. A graphical presentation of the obtained global weights by the sub-criteria is shown in Figure 1.

Table 5. Global weights of the sub-criteria

Criteria Code	Weights	Sub-Criteria Code	Weights	Finalized Global Weights	Rank
P	0.132	P1	0.159	0.021	14
		P2	0.467	0.062	7
		P3	0.267	0.035	13
		P4	0.108	0.014	15
M	0.293	M1	0.128	0.038	12
		M2	0.160	0.047	10
		M3	0.293	0.086	4
		M4	0.271	0.079	5
		M5	0.149	0.044	11
C	0.237	C1	0.530	0.126	2
		C2	0.217	0.051	9
		C3	0.252	0.060	8
H	0.338	H1	0.535	0.181	1
		H2	0.265	0.090	3
		H3	0.200	0.068	6

For this study, 5 PB (18 mm thickness, jute-based, Urea Formaldehyde binder) have been evaluated with the proposed method from 5 different PB manufacturers in Bangladesh. Subjective criteria have been evaluated by aggregating experts' opinions using the previously mentioned scale in Table 3. The laboratory test value of the objective criteria and evaluating scores of the subjective criteria for the 5 PB brands (PB1 to PB5) can be found in Table 6.

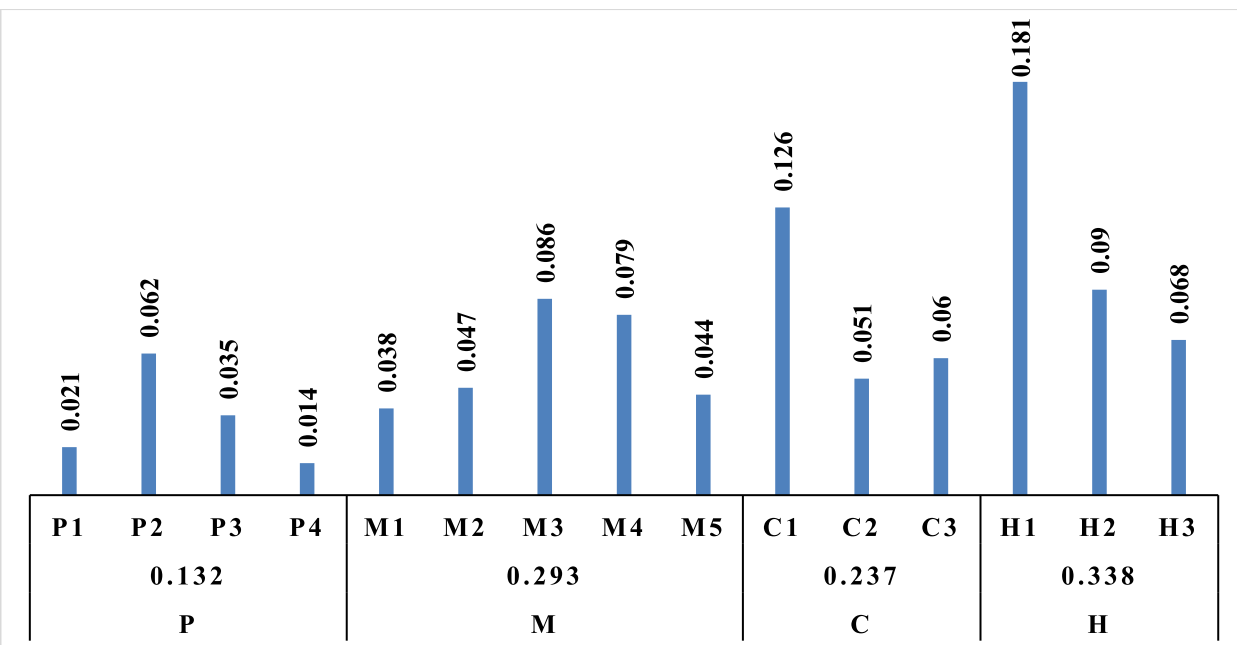

Figure 1: Global weights of the sub-criteria

Table 6. Test result and experts' scores for the collected PBs

Brands	P1 (mm)	P2 (Kg/m^3)	P3 (%)	P4	M1 (N/mm^2)	M2 (N/mm^2)	M3 (N)	M4 (N/mm^2)	M5 (N/mm^2)	C1 (%)	C2	C3	H1 ($mg/m^2.hr$)	H2	H3
PB1	18.11	554	2	3	13.39	1545	575	0.37	0.81	8.0	3	2	2.0	2	1
PB2	18.32	545	4	4	12.12	1542	564	0.39	0.82	8.0	4	3	2.3	2	3
PB3	17.97	558	3	2	13.01	1537	560	0.38	0.76	7.5	3	3	2.4	3	4
PB4	17.98	552	5	3	12.98	1540	572	0.37	0.79	7.8	2	2	2.1	2	1
PB5	18.28	553	4	3	13.09	1533	569	0.39	0.78	8.5	3	4	2.0	3	1

Sub-criteria based on their beneficial and non-beneficial characteristics are separated in Table 7. For separating beneficial and non-beneficial sub-criteria, P1 (Thickness) and P2 (Density) need to be treated in a separate way than other sub-criteria. For these two, distances from ideal values have been considered. The more the distances are, the less the scores are obtained.

Table 7. Division of sub-criteria characteristically

Beneficial	**Non-beneficial**
P1, P2, P3, C1, H1, H2, H3	P4, M1, M2, M3, M4, M5, C2, C3

The normalized decision matrix extracted from Table 6 has been shown in Table 8.

Table 8. Normalized decision-matrix

Brands	P1	P2	P3	P4	M1	M2	M3	M4	M5	C1	C2	C3	H1	H2	H3
PB1	0.200	0.500	1.000	0.750	1.000	1.000	1.000	0.949	0.988	0.938	0.750	0.500	1.000	1.000	1.000
PB2	0.067	0.400	0.500	1.000	0.905	0.998	0.981	1.000	1.000	0.938	1.000	0.750	0.870	1.000	0.333
PB3	0.667	0.250	0.667	0.500	0.972	0.995	0.974	0.974	0.927	1.000	0.750	0.750	0.833	0.667	0.250
PB4	1.000	1.000	0.400	0.750	0.969	0.997	0.995	0.949	0.963	0.962	0.500	0.500	0.952	1.000	1.000
PB5	0.067	0.667	0.500	0.750	0.978	0.992	0.990	1.000	0.951	0.882	0.750	1.000	1.000	0.667	1.000

Global weights of the evaluation criteria from Table 5 have been used to derive the Weighted Normalized Decision Matrix. Finally obtained evaluation scores for the ranking of the PBs with WPM can be seen in Table 9. This result shows that PB4 is the best PB brand among the 5 alternatives according to the mixed method calculation (both laboratory test and expert opinion-based values).

Table 9. Weighted normalized decision matrix with finalized scores by WPM

Brands	P1	P2	P3	P4	M1	M2	M3	M4	M5	C1	C2	C3	H1	H2	H3	**Scores**	**Rank**
PB1	0.9668	0.9582	1.0000	0.9959	1.0000	1.0000	1.0000	0.9958	0.9995	0.9919	0.9853	0.9594	1.0000	1.0000	1.0000	**0.861**	**2**
PB2	0.9447	0.9451	0.9759	1.0000	0.9963	0.9999	0.9983	1.0000	1.0000	0.9919	1.0000	0.9830	0.9750	1.0000	0.9284	**0.765**	**4**
PB3	0.9915	0.9181	0.9858	0.9902	0.9989	0.9998	0.9977	0.9979	0.9967	1.0000	0.9853	0.9830	0.9676	0.9643	0.9105	**0.725**	**5**
PB4	1.0000	1.0000	0.9682	0.9959	0.9988	0.9998	0.9996	0.9958	0.9984	0.9951	0.9650	0.9594	0.9912	1.0000	1.0000	**0.874**	**1**
PB5	0.9447	0.9753	0.9759	0.9959	0.9992	0.9996	0.9991	1.0000	0.9978	0.9844	0.9853	1.0000	1.0000	0.9643	1.0000	**0.834**	**3**

4. Results and Discussion

Most of the experts evaluated the 'Health and Environmental Impact' of PB as a prime concern for PB selection. Because of such evaluation, this criterion gets the most weightage (0.338) among all the criteria. The high emission level of formaldehyde, anti-termite, and anti-fungal hazardous chemicals used in PB manufacturing, and the chemical odor emitted from the finisher PB can be harmful to the environment and health of the end-users. 'Mechanical Properties' criterion gets the second-highest weightage (0.293). Different strength criteria of PB depend on its mechanical properties and make the product usable and durable for construction projects and other uses. The remaining two criteria 'Chemical Properties' and 'Physical Properties' are weighted as 0.237 and 0.132 respectively. Chemical properties largely depend on moisture content and characteristics of base and binding materials. Physical properties like thickness, density, swelling, and color are highly dependent on all the other criteria as well as on the treatment and methods used for PB manufacturing. The higher the weightage of a criterion, the more influential it is over other criteria for selecting PB.

After getting the criteria weights, sub-criteria weights have been determined in this study (see Table 5). The criteria and sub-criteria described in this study are used to cluster the evaluation criteria into distinct groups. The top 5 evaluation criteria of PB as per their weights obtained from BWM are H1 (Emission Level) > C1 (Moisture Content) > H2 (Toxicity) > M3 (Screw Withdrawal Strength) > M4 (Surface Soundness). Formaldehyde **emission** from resin is one of the most discussed issues for decades in the PB industry all over the world. This specific emission can create severe health and environmental hazard (Zhang et al., 2018**)**. This evaluation criterion has been figured out as the most important criteria for PB selection. Moisture content is the second most important criterion for the selection of a PB product. Even though 'Chemical Properties' has been ranked as the third most important criteria, a sub-criterion of this criterion, 'Moisture Content', has obtained the second-highest globalized weight among all the evaluation criteria, which is an interesting observation about the obtained result. The presence of water or other liquid chemicals beyond the acceptable limit in PB can highly affect all other physical and mechanical properties. This criterion can be an important reason behind less strength, early damage, internal crack, swelling, and such other major quality hampers of PB after short time usage. Toxicity is the third most important criterion as per the achieved weightage, which is again a factor of health and environmental hazard. Toxicity occurs due to the excessive use of non-standard anti-termite and anti-fungal chemicals during PB manufacturing. The next two evaluation criteria of the five top-ranked criteria are **Screw** Withdrawal Strength and Surface Soundness, both of which are mechanical properties of PB. Mechanical screws are used as a threaded fastener for joining multiple PBs to construct different structures. Besides this, the surface of a PB is laminated and glued very often to join with another PB for making fixtures, furniture, etc. structures, for which a sound and strong surface is required. As PB is mainly used for construction projects, furniture, and door manufacturing; screw withdrawal strength and surface soundness are very important to achieve the best durability of the finished products.

Using the obtained weights of evaluation criteria from BWM, 5 brands have been evaluated by the WPM method in this study. The obtained product or brand priority ranking is (see Table 9) PB4 (0.874)> PB1(0.861)> PB5(0.834)> PB2(0.765)> PB3(0.725). As the PB brand, 'PB4' has obtained the best ranking score, this brand has been selected as the best PB for construction projects or furniture manufacturing. A comparison of the brands according to their obtained score in different evaluation criteria has been shown in Figure 2. Based on the insights obtained in Figure 2, getting an optimized score in all the highly weighted evaluation criteria can be more important for selection, rather than getting outlier scores in specific one or two criteria.

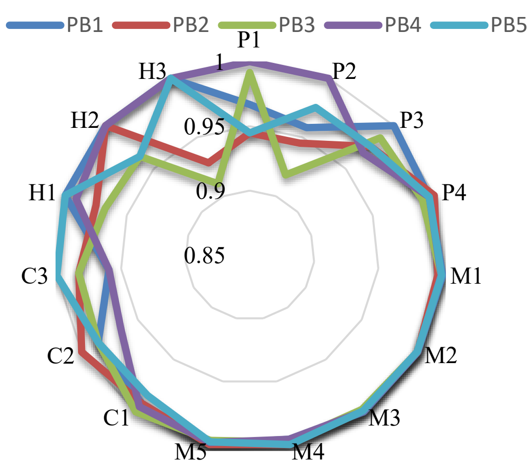

Figure 2. Radar Chart demonstrating a comparison of the brands

5. Managerial Implications

Obtained results have been discussed with several industrial managers to have a better understanding of the implications of the conducted study. Managers working in different construction and furniture industries who need to select PB for their projects can obtain valuable insights from this study. For example, as a profitable and booming industry, PB is manufactured from various base and binding materials with numerous characteristics. PB manufactured by assorted brands offers different criteria to verify their quality. But all the evaluation criteria do not have the same weightage when PB is needed to be selected to be used in the construction projects or furniture manufacturing. Since this research identifies the significant evaluation criteria to evaluate and select PB, it will help the managers to be more conscious of the evaluation criteria while deciding to select the best PB for their projects. Laboratory testing methods and international standards have also been mentioned in this study, which will help the managers to make an empirical decision rather than going for only subjective decisions in the case of PB selection.

6. Conclusion

PB is an important industrial product to make the environment more sustainable by reducing deforestation. In this study, a hybrid BWM-WPM technique has been applied to evaluate and rank PBs from different manufacturers. BWM is comparatively a simpler pairwise-comparison MCDM technique, where experts do not need to make a comparison among all the criteria, rather they need to focus only on the best and the worst criteria. This is helpful to bring a consistent solution from the experts' evaluation. WPM is a simple method as well, which has been applied here using the weights obtained from BWM, to select the best product.

This study shows that construction managers and supervisors need to be more focused on the health and environmental impact of PB while selecting for their projects besides the mechanical, chemical, and physical properties to ensure the best quality PB. Formaldehyde emission level, moisture content, toxicity due to hazardous chemicals, screw withdrawal strength, and surface soundness are the most important selection criteria for PB to be used in construction projects. An interesting observation from this study is that even though 'Chemical Properties' has been ranked as the third most important criteria, a sub-criterion of this criterion, 'Moisture Content', has obtained the second-highest globalized weight among all the evaluation criteria, as it can affect all other mechanical and physical properties of the PB. In this study, the final selection of PB from multiple alternatives shows that the brand which has achieved an optimized score in all the evaluation criteria ultimately gets selected. This indicates that the project managers need to emphasize selecting PB, which fulfills all the evaluation criteria at an optimum level. That is, scoring very high in some criteria, then scoring low on other criteria might not be helpful for final selection. This research has hence been expected to be helpful to make the decision-makers more conscious about the selection criteria of PB and the manufacturer to develop the product which will score high in all these evaluation criteria.

In the future, other MCDM techniques can also be applied for this specific study and a comparative study can be conducted with the results obtained from different methods. This proposed methodology can also be redesigned for other areas of MCDM studies, where decision-makers need to take critical decisions in a multi-dimensional environment. Finally, this mathematical framework for selecting PB can be converted to computer-based software which can make the overall procedure simpler and less time-consuming.

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Supplementary Materials

Appendix A

Table 1A: Sample of the Expert Opinion Collection Form (with Response from Ex-1)

Questionnaire for Finding Criteria Weights	
What is the 'Most Important' criterion to select a PB?	☐ Physical Properties (P) ☐ Mechanical Properties (M) ☐ Chemical Properties (C) ☒ Health and Environmental Impact (H)
How many times are your 'Most Important' criterion comparatively important over other criteria? (1 for equal importance and 9 for extremely importance)	P 1☐ 2☐ 3☒ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ M 1☐ 2☒ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ C 1☐ 2☒ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ H 1☒ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐
What is the 'Least Important' criterion to select a PB?	☒ Physical Properties (P) ☐ Mechanical Properties (M) ☐ Chemical Properties (C) ☐ Health and Environmental Impact (H)
How many times are other criteria comparatively important over your 'Least Important' criterion? (1 for equal importance and 9 for extremely importance)	P 1☒ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ M 1☐ 2☒ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ C 1☐ 2☒ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ H 1☐ 2☐ 3☒ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐

Table 2A: Standard Value of the Objective Evaluation Criteria for Jute-based PB (18-mm thickness)

Objective Evaluation Criteria	International Test Method	Standard Value	Reference International Code
Thickness	N/A	18 mm	(BS-5669-2, 1989)
Density	(EN 323, 1993)	550 kg/m^3	
Swelling (after 1 hour at 20°C)	(BS-5669-2, 1989)	Maximum 8%	
Bending Strength (BS)	(EN 310, 1993)	Minimum 9 N/mm^2	
Modulus of Elasticity (MOE)	(EN 310, 1993)	Minimum 1100 N/mm^2	
Screw Withdrawal Strength (SWS)	(EN 320, 2011)	Minimum 360 N	
Surface Soundness (SS)	(EN 311, 2004)	Minimum 0.65 N/mm^2	
Tensile Strength (TS)	(EN 319, 1996)	Minimum 0.34 N/mm^2	
Moisture Content	(EN 322, 1996)	Maximum 15%	
Emission Level	(EN 717-2, 2012)	E_1 (max 3.5 mg/m2.h)	(EN 717-2, 2012)

Table 3A: Weights of Sub-Criteria

Sub-Criteria Code		**Ex-1**	**Ex-2**	**Ex-3**	**Ex-4**	**Ex-5**	**Ex-6**	**Ex-7**	**Ex-8**	**Ex-9**	**Aggregated Weights**	**Normalized Weights**
P	**P1**	0.226	0.170	0.138	0.136	0.169	0.125	0.150	0.103	0.211	0.154	**0.159**
	P2	0.419	0.468	0.379	0.394	0.569	0.344	0.550	0.483	0.526	0.453	**0.467**
	P3	0.226	0.255	0.414	0.394	0.169	0.375	0.200	0.276	0.158	0.259	**0.267**
	P4	0.129	0.106	0.069	0.076	0.092	0.156	0.100	0.138	0.105	0.105	**0.108**
	Ksi*	0.032	0.043	0.034	0.015	0.108	0.031	0.050	0.069	0.105		
M	**M1**	0.143	0.214	0.125	0.105	0.133	0.091	0.125	0.112	0.105	0.124	**0.128**
	M2	0.214	0.143	0.188	0.184	0.100	0.145	0.188	0.131	0.147	0.156	**0.160**
	M3	0.286	0.286	0.292	0.184	0.333	0.400	0.292	0.196	0.379	0.286	**0.293**
	M4	0.214	0.214	0.292	0.342	0.267	0.218	0.292	0.364	0.221	0.264	**0.271**
	M5	0.143	0.143	0.104	0.184	0.167	0.145	0.104	0.196	0.147	0.145	**0.149**
	Ksi*	0.071	0.071	0.083	0.026	0.067	0.036	0.083	0.028	0.063		
C `	**C1**	0.690	0.629	0.542	0.550	0.633	0.600	0.667	0.200	0.250	0.490	**0.530**
	C2	0.143	0.143	0.167	0.200	0.200	0.167	0.143	0.300	0.550	0.201	**0.217**
	C3	0.167	0.229	0.292	0.250	0.167	0.233	0.190	0.500	0.200	0.234	**0.252**
	Ksi*	0.024	0.057	0.042	0.050	0.033	0.100	0.095	0.100	0.050		
H	**H1**	0.542	0.500	0.400	0.571	0.650	0.333	0.542	0.633	0.563	0.516	**0.535**
	H2	0.292	0.300	0.200	0.286	0.225	0.222	0.292	0.200	0.313	0.255	**0.265**
	H3	0.167	0.200	0.400	0.143	0.125	0.444	0.167	0.167	0.125	0.193	**0.200**
	Ksi*	0.042	0.100	0.000	0.000	0.025	0.111	0.042	0.033	0.063		