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Optimizing Material Selection for Automotive Piston Components Using a Multi-Criteria Decision-Making Approach

***Sathiyaraj Chinnasamy, M. Ramachandran, Chinnasami Sivaji, Manjula Selvam**
REST Labs, Kaveripattinam, Krishnagiri, Tamil Nadu, India
*Corresponding Author Email: sathiyaraj@restlabs.in

Abstract: *Piston component material choices for automobiles plays a crucial role in ensuring engine performance, durability, and efficiency. Several factors are considered when choosing these materials. Firstly, high strength and wear resistance are essential to withstand the demanding conditions within the engine cylinder. Aluminium alloys with outstanding strength-to-weight ratios and thermal conductivity, including Al-Si, Al-Si-Cu, and other combinations of aluminium, silicon, and copper are frequently used in construction. Secondly, thermal stability is vital to withstand high operating temperatures. Materials like cast iron and steel alloys are favored for their superior heat resistance. Thirdly, low friction and good lubrication properties are necessary for efficient engine operation. For this purpose, materials with surface treatments such as thermal spray coatings or friction-reducing coatings are employed. Lastly, considerations for cost, manufacturability, and environmental impact also influence material selection. Therefore, a comprehensive evaluation of mechanical properties, thermal stability, friction characteristics, and overall cost-effectiveness guides the selection process for automotive piston components. The research significance of Material selection for Automotive piston components lies in its direct impact on engine performance, efficiency, and durability. Optimizing the choice of materials can lead to enhanced fuel economy, reduced emissions, and increased engine longevity. By conducting research in this field, several key advancements can be achieved. Firstly, exploring new materials or alloy compositions can result in improved mechanical properties, allowing for higher engine power outputs without compromising reliability. This can lead to the development of more efficient and high-performance engines. Secondly, investigating surface treatments and coatings can reduce friction and wear, resulting in reduced energy losses and increased engine efficiency. Furthermore, it can contribute to the development of environmentally friendly engines with lower emissions. Lastly, considering the cost-effectiveness of materials and their manufacturing processes can lead to more affordable and accessible automotive technologies, benefiting both manufacturers and consumers. Overall, research in Material selection for Automotive piston components holds significant potential for advancing engine technology, improving environmental sustainability, and enhancing the overall driving experience. This uses the multi-criteria decision-making approach known as Weighed Aggregated Sum Product Assessment. It entails giving several criteria weights and evaluating options in accordance with those criteria. Each alternative is given a score based on its weights, and the alternative with the greatest score is deemed to be the most favourable. It helps in decision-making processes where multiple criteria need to be considered simultaneously. Alternative Parameters taken as "Porcelain, LM-26 alloy +0 wt.%, and LM-26 alloy +2 wt.% Porcelain, +4 wt% LM-26 alloy Porcelain with LM-26 alloy added to it by either 6% or 8% Porcelain" Evaluation Parameters taken as "Hardness (Hv), Density (g/cc), Tensile strength (MPa), Compressive strength (MPa), and Flexural strength (MPa) With a load of 45 N, a speed of 3.768 m/s, and a friction coefficient of (), the specific wear rate (in mm3/N-m) is calculated. 3.768 m/s is the speed." This demonstrates the rank of the data set LM-Alloy (+6 wt.% Porcelain, is on 1st rank, +4 wt.% Porcelain, is on 2nd rank, +8 wt.% Porcelain, is on 3rd rank, +2 wt.% Porcelain, is on 4th rank, +0 wt.% Porcelain, is on 5th rank). The choice of material for automotive piston components is crucial in influencing the effectiveness and performance of an engine as a whole. Several factors are considered when choosing the appropriate materials. Strength is crucial to withstand the high pressures and temperatures inside the combustion chamber. Heat resistance is necessary to prevent thermal expansion and maintain dimensional stability. Durability is essential to withstand the repetitive loading cycles and resist wear and tear. Additionally, weight is a significant consideration for improving fuel efficiency and reducing emissions. In conclusion, the careful selection of materials for automotive piston components is crucial in achieving optimal engine performance, durability, and fuel efficiency.*

Keywords: *Manufacturing, ranking, and MCDM (Multiple Criteria Decision Making) ,SM (Weighted Sum Model), WASPAS (Weighted Aggregated Sum Product Assessment), and WPM (Weighted Product Model).*

1. INTRODUCTION

The 21st-century automobile, much like its predecessors over the past century, will be shaped by three main factors: consumer preferences, manufacturers' capabilities, and government regulations [3]. Selecting an appropriate material for a mechanical component in engineering applications poses a challenging task for designers. When selecting the best material, a number of factors must be taken into account, such as the material's surface properties, machinability, cost, dependability, durability, and ability to be recycled, as well as its mechanical, physical, magnetic, electrical, thermal, and radiation properties, availability, fashion, market trends, cultural considerations, and other pertinent elements. This selection process is time-consuming and requires careful consideration [2]. The piston, a crucial component of reciprocating internal combustion engines, resides within a cylinder and, with the assistance of piston rings, ensures a sealed environment for efficient combustion processes [5]. It is worth noting that the piston is subjected not only to pressure but also to significant temperature effects, which can lead to severe damage and overheating [6]. While aluminum has been used in automobile intake manifolds, gearbox housings, and heads for more than 50 years, its widespread application as a block material is more recent [4]. Due to their high strength-to-weight ratio, enhanced hardness and wear resistance, improved damping capability, and reduced coefficient of thermal expansion, these materials perform exceptionally well in automotive applications [1].

A classic industrial product that uses a range of components and technology is the vehicle. To match present-day societal demands, it is necessary to use relatively lighter materials when making vehicles. However, a modern car still contains between 70% and 80% of iron and steel, despite the rising use of aluminium and plastic. The optimum material for use in extremely resilient, highly stressed components is metal.How effectively a certain application's processing technology performs directly affects the level of functionality and component performance.[7] Conventional pistons composed of aluminum-silicon alloys are also produced, but the seats for the piston rings are cast-in components constructed of an aluminium composite with aluminium oxide reinforcement. Since 1981, "Metal Matrix Composite Engine pistons" have only been used by Toyota. The business for diesel engine pistons began with the introduction of very straightforward Alumina-silica fibers, which are squeeze-cast into the tops of Al alloy pistons. [8] Valve covers, intake manifolds, alternator housing, timing belt/chain convers, alternator brackets, gearbox housing, and alternator housing made of aluminum fly-ash composites would have better emissions and performance while costing less and adding less weight to the car. Lower friction coefficients and wear rates were noticed when aluminum-graphite pistons and liners were tested in gasoline and diesel engines as well as racing automobiles.[9]

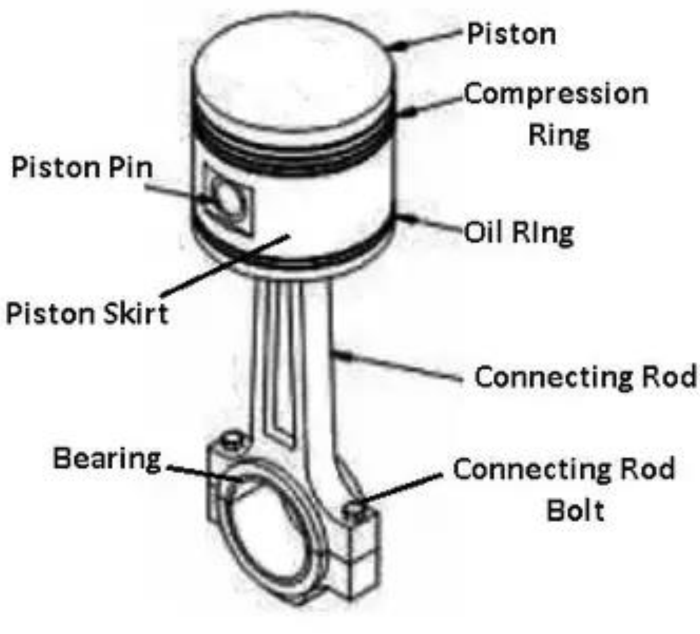

FIGURE 1. Piston

The free piston engine is made up of a liner alternator, a double-ended cylinder, and a double-ended piston, among other parts. The double-ended cylinder's piston is free to travel in any direction along the cylinder's axis [20]. Due to their better creep, fatigue, and wear resistances, low density, high strength-to-weight ratio, and high temperature strength retention, metal matrix composites (MMCs) have the potential to replace materials like cast iron in engines and brakes. MMCs commonly used in automotive applications include silicon carbide (SiC), aluminum oxide (Al2O3), or other ceramic particles or short fibers embedded in lightweight alloys such as titanium, magnesium, or aluminum. “For a variety of engine parts, including diesel engine pistons, cylinder liners, brake drums, and brake rotors, MMCs have been created. Although the expense of using them has been investigated for possible uses including drive shafts, piston pins, and connecting rods, it is still a major barrier to their widespread use [12]. Despite being attached to the engine piston, piston rings were first created as a separate part to aid in sealing and prevent gas leaks from the combustion chamber [19]. Lightweight composite materials with high specific strength, stiffness, temperature resistance, low thermal coefficient, wear resistance, and thermal conductivity have a lot of potential for use in car engines.” The piston rod, piston, and its pin are a few examples of such parts, as well as the valve train. Since the strength and hardness of alloys are primarily dependent on their microstructure, great work has been put into refining the microstructure of castings in order to improve the mechanical characteristics of aluminum [17]. Through the use of a crankshaft and connecting rod, a piston functions by converting reciprocating motion into rotating motion [18].

2. MATERIALS &METHODS

Alternative parameters:

LM-26 alloy +0 wt.% Porcelain: Due to its high strength, superior wear resistance, and exceptional thermal stability, LM-26 alloy is used for automobile piston components. Adding 0 wt.% porcelain improves its performance by enhancing hardness, reducing friction, and increasing the resistance to thermal expansion, resulting in better overall piston performance.

LM-26alloy+2wt.% Porcelain: LM-26 alloy, combined with 2 wt.% porcelain, is an ideal choice for automotive piston components. The alloy provides high strength, wear resistance, and thermal stability, while the addition of porcelain further enhances hardness, reduces friction, and improves resistance to thermal expansion, resulting in superior piston performance.

LM-26 alloy +4 wt.% Porcelain: LM-26 alloy, with an additional 4 wt.% of porcelain, is a highly suitable material for automotive piston components. The alloy's inherent strength, wear resistance, and thermal stability are further improved by the porcelain, which enhances hardness, reduces friction, and increases resistance to thermal expansion, resulting in exceptional piston performance.

LM-26 alloy +6 wt.% Porcelain: LM-26 alloy, augmented with 6 wt.% porcelain, is an optimal choice for automotive piston components. The alloy's strength, wear resistance, and thermal stability are significantly enhanced by the porcelain, which boosts hardness, minimizes friction, and augments resistance to thermal expansion, resulting in superior piston performance.

LM-26 alloy +8 wt.% Porcelain: LM-26 alloy, combined with 8 wt.% porcelain, is an excellent material for automotive piston components. The porcelain addition further enhances the alloy's strength, wear resistance, and thermal stability, contributing to improved hardness, reduced friction, and increased resistance to thermal expansion, resulting in superior piston performance.

Evaluation parameters:

Hardness (Hv): Hardness (Hv) is a crucial property in materials for automotive piston components. A high Hv ensures resistance to wear and deformation under the harsh conditions of engine operation, contributing to the durability and longevity of the piston, ultimately improving overall engine performance and reliability.

Compressive strength (MPa): Compressive strength (MPa) is vital for materials used in automotive piston components. It measures the ability of the material to withstand compression forces without deformation or failure. High compressive strength ensures the piston can withstand the intense pressures within the engine cylinder, ensuring reliable and efficient engine performance.

Tensile strength (MPa): Tensile strength (MPa) is a critical property for materials in automotive piston components. It measures the material's ability to resist forces that pull it apart. High tensile strength ensures the piston can withstand the tensile stresses generated during engine operation, ensuring the integrity and reliability of the piston under high loads and temperatures.

Flexural strength (MPa): Flexural strength (MPa) is significant for materials in automotive piston components. It measures the material's ability to withstand bending or flexing forces without breaking. High flexural strength ensures the piston can withstand the dynamic and cyclic loads experienced during engine operation, contributing to its durability and longevity.

Density (g/cc): Density (g/cc) is an important property for materials used in automotive piston components. Low-density materials are desirable as they reduce the overall weight of the piston, improving engine efficiency and reducing fuel consumption. Additionally, lower density materials can contribute to improved thermal management and reduced friction within the engine.

Specific wear rate (in mm3/N-m) at 45 N of load and 3.768 m/s of speed: Specific wear rate (in mm^3/N-m) at a load of 45 N of load and velocity of 3.768 m/s of speed is a critical factor for materials used in automotive piston components. Low specific wear rate indicates minimal material loss during sliding contact, ensuring longevity, reliability, and reduced maintenance of the piston assembly in the engine.

Friction coefficient () with 45 N of load and 3.768 m/s of speed: Friction coefficient (μ) at a load of 45 N and velocity of 3.768 m/s of speed is a crucial parameter for materials used in automotive piston components. A low friction coefficient ensures reduced energy loss and efficient power transfer, minimizing wear, heat generation, and improving overall engine performance and fuel efficiency.

WASPAS Method: Multi-criteria decision-making (MCDM) techniques are regarded as important resources for examining and resolving challenging real-time problems. These methods possess the inherent capability to evaluate numerous options based on various criteria, aiming to identify the optimal alternative [2]. Among the emerging MCDM utility determining algorithms, WASPAS has garnered considerable attention since its introduction in 2012. Zavadskas, Turskis, Antucheviciene, and Zakarevicius have demonstrated that this method, which combines the Weighted Product Model (WPM) and Weighted Sum Model (WSM), exhibits superior accuracy when compared to WPM and WSM [1]. Therefore, the main goal of any MCDM approach is to choose the best choice from a collection of realistic options while taking into account several conflicting criteria [3].

The advantage of employing a fuzzy method over relying simply on precise numbers is that fuzzy numbers can be used to establish the relative importance of attributes. The fuzzy WASPAS technique, which has never been used to solve issues of this kind, is used in our particular example. [4]. The WASPAS approach successfully integrates the Weighted Sum Model (WSM) and the Weighted Product Model (WPM), two well-known methodologies. The WASPAS method is used in this circumstance to evaluate and rank the possibilities, while other decision-making disciplines may use different techniques [5] [10].

The WASPAS technique further develops and applies the following more generalised equation to ascertain the overall relative relevance of the ith alternative in order to improve ranking accuracy and the effectiveness of the decision-making process:

$$Q_i = \lambda Q_i^{(1)} + (1-\lambda) Q_i^{(2)} = \lambda \sum_{j=1}^{n} \bar{x}_{ij} w_j +$$

$$(1-\lambda) \prod_{j=1}^{n} (\bar{x}_{ij})^{w_j}, \ \lambda = 0, 0.1, \ldots, 1.$$

The best option is determined by the candidate alternatives' Q values, which are used to rank them. When a particular parameter's value is set to 0, the WASPAS approach can be changed into a Weighted Product Model (WPM), and when the value is set to 1, it can be transformed into a Weighted Sum Model (WSM). The WASPAS technique has been used to improve ranking accuracy when resolving multi-criteria decision-making (MCDM) difficulties by reaching the highest estimation accuracy. [8]. As explained by Zavadskas et al. in 2012 [11], the Weighted Aggregated Sum Product Assessment (WASPAS) technique maintains the optimisation of aggregation during the evaluation of alternatives. Options may be ranked according to their Q values, with the option with the highest Q value being regarded as the best. The WASPAS method is equivalent to WPM when the parameter is set to 0, and it is equivalent to WSM when the parameter is set to 1 [12]. In recent years, scholars have suggested integrating or combining the SWARA and WASPAS methodologies to address various problems [7]. The Waspas strategy offers decision-makers a methodical and structured approach to take into account many criteria and their respective importance, helping to mitigate personal biases and providing a clear framework for evaluating options. It is important to ensure the accuracy and appropriateness of the criteria, weights, and performance ratings provided to obtain reliable results when using the Waspas technique [10].

3. RESULTS & DISCUSSION

Table 1. Material selection for Automotive Piston Component

Piston material	C1	C2	C3	C4	C5	C6	C7
LM-26 alloy +0 wt.% Porcelain	102	37.42	150.6	168.78	2.753	0.000279	0.067
LM-26 alloy +2 wt.% Porcelain	104.5	41.37	161.8	197.94	2.746	0.000263	0.063
LM-26 alloy +4 wt.% Porcelain	106.9	43.37	168.8	242.97	2.738	0.000246	0.059
LM-26 alloy +6 wt.% Porcelain	109.9	46.4	181	281.71	2.73	0.000167	0.05
LM-26 alloy +8 wt.% Porcelain	112.3	39.19	157	218.56	2.712	0.000249	0.073

Table 1 presents the different alternatives consisting of LM-26 alloy combined with varying weight percentages of porcelain: "LM-26 alloy +0 wt% Porcelain, LM-26 alloy +2 wt% Porcelain, LM-26 alloy +4 wt% Porcelain, LM-26 alloy +6 wt% Porcelain, and LM-26 alloy +8 wt% Porcelain. The evaluation of porcelain includes several parameters such as hardness (Hv), compressive strength (MPa), tensile strength (MPa), flexural strength (MPa), density (g/cc), specific wear rate (in mm3/N-m) at a load of 45 N and a velocity of 3.768 m/s, as well as the friction coefficient at a load of 45 N and a velocity of 3.768 m/s."

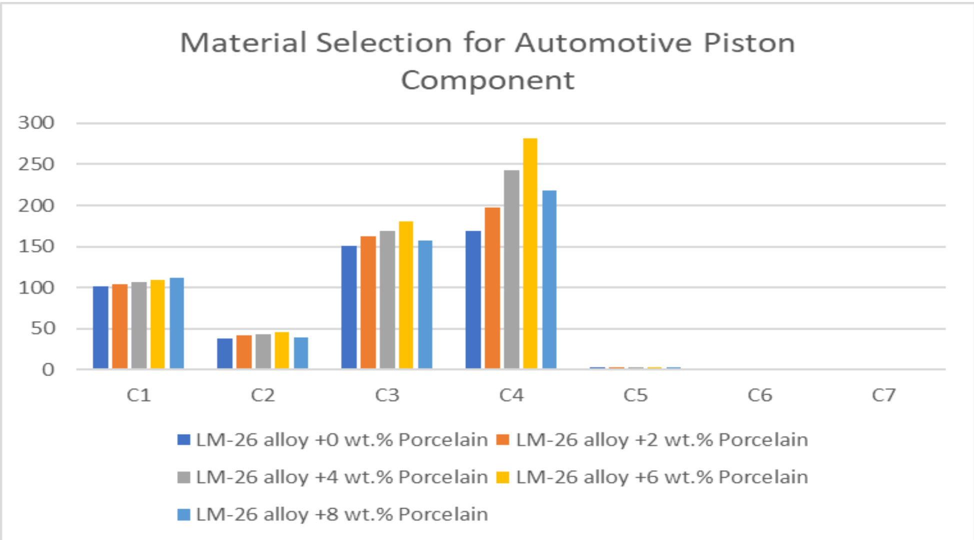

FIGURE 1. Material selection for Automotive Piston Component

Figure 1 presents the different alternative parameters and evaluation parameters.

Table 2. Normalized Data

Normalized data						
0.909	0.806	0.832	0.599	0.985	0.599	0.746
0.931	0.892	0.894	0.703	0.988	0.635	0.794
0.953	0.935	0.933	0.862	0.991	0.679	0.847
0.979	1.000	1.000	1.000	0.993	1.000	1.000
1.000	0.845	0.867	0.776	1.000	0.671	0.685

Table 2 shows normalized data of Alternative and Evaluation parameters.

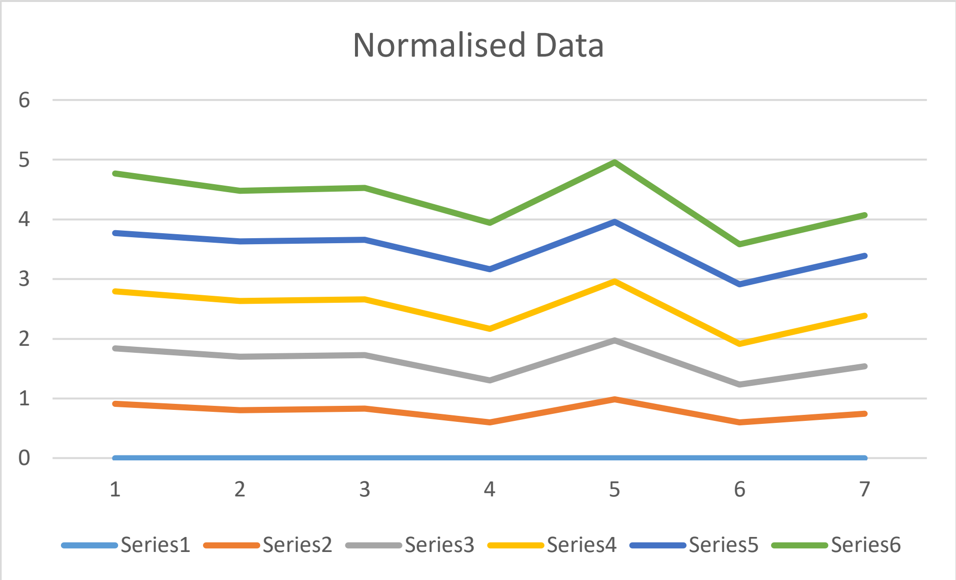

FIGURE 2. Normalized Data

Figure 2 shows the normalised data ofAlternative and Evaluation parameters. Table 3 Weight shows the informational set for the weight all same value 0.143

Table 4. Weighted Normalised Decision Matrix (WSM)

Weight normalised decision matrix (wsm)						
0.130	0.115	0.119	0.086	0.141	0.086	0.107
0.133	0.127	0.128	0.100	0.141	0.091	0.113
0.136	0.134	0.133	0.123	0.142	0.097	0.121
0.140	0.143	0.143	0.143	0.142	0.143	0.143
0.143	0.121	0.124	0.111	0.143	0.096	0.098

Table 4 shows the normalised decision matrix with weights of alternative and evaluation parameters.

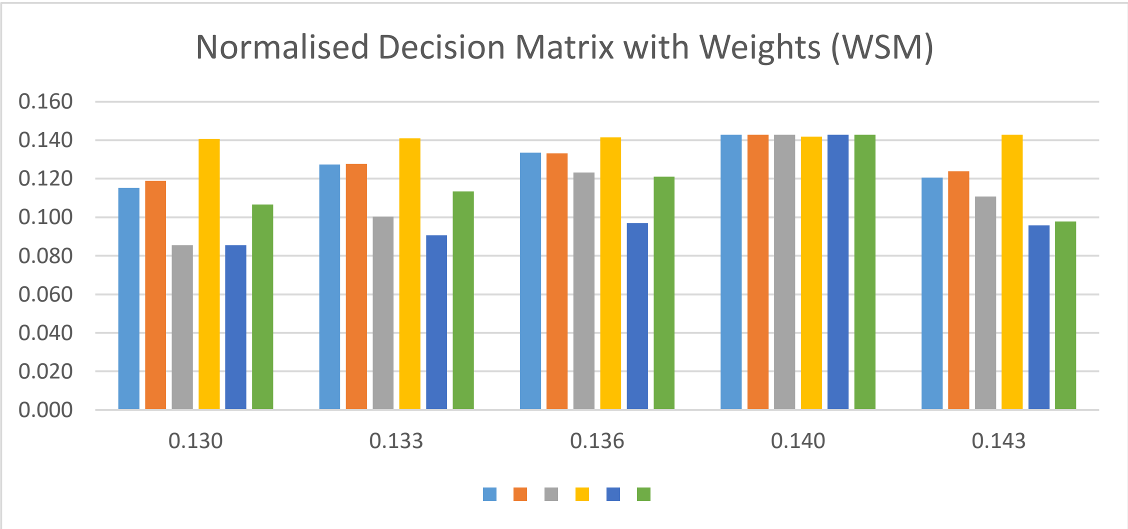

FIGURE 3. Normalised Decision Matrix with Weights (WSM)

Figure 3 shows the Normalised Decision Matrix with Weights (WSM) of differentAlternative and Evaluation parameters.

Table 5: Weighted Normalised Decision Matrix (WPM)

Weight Normalised Decision Matrix (Wpm)						
0.986	0.970	0.974	0.929	0.998	0.929	0.959
0.990	0.984	0.984	0.951	0.998	0.937	0.968
0.993	0.990	0.990	0.979	0.999	0.946	0.977
0.997	1.000	1.000	1.000	0.999	1.000	1.000
1.000	0.976	0.980	0.964	1.000	0.945	0.947

Table 5 shows the Normalised Decision Matrix with Weights (WPM) of alternative and evaluation parameters.

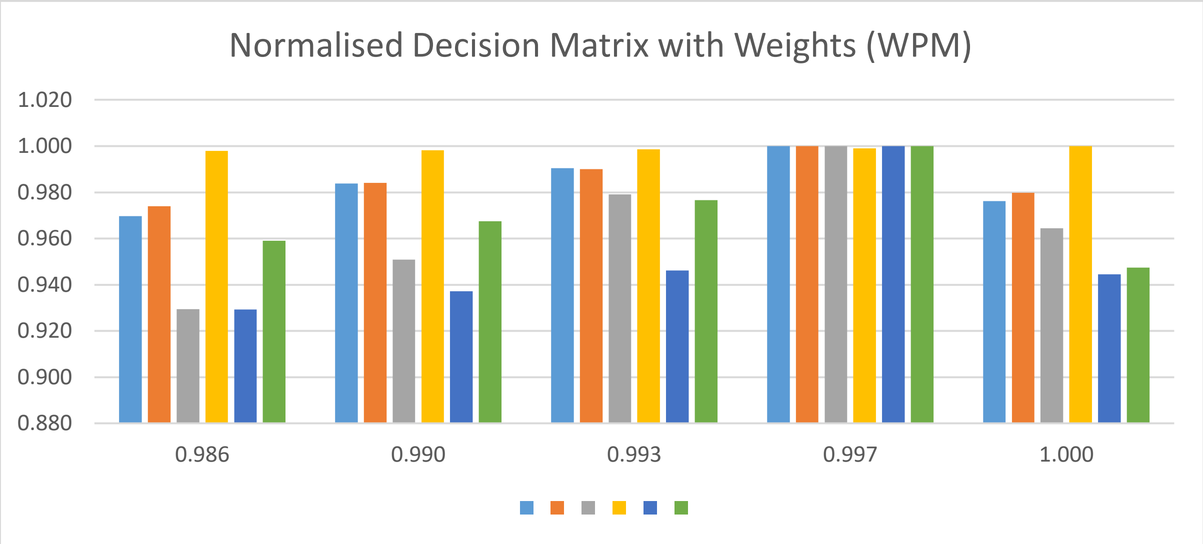

Figure 4 Normalised Decision Matrix with Weights (WPM)

Figure 4 shows the Weighted Normalised Decision Matrix of Alternative and Evaluation parameters.

TABLE 6. Preference Score (WSM, WPM) & WASPAS Coefficient

Preference score(wsm)	**Preference score(wpm)**	**Waspas coefficient**
0.782	0.770	0.776
0.834	0.825	0.829
0.886	0.880	0.883
0.996	0.996	0.996
0.835	0.825	0.830

Table 6 shows the preference score (WSM,WPM) & WASPAS Coefficient of alternative and evaluation parameters.

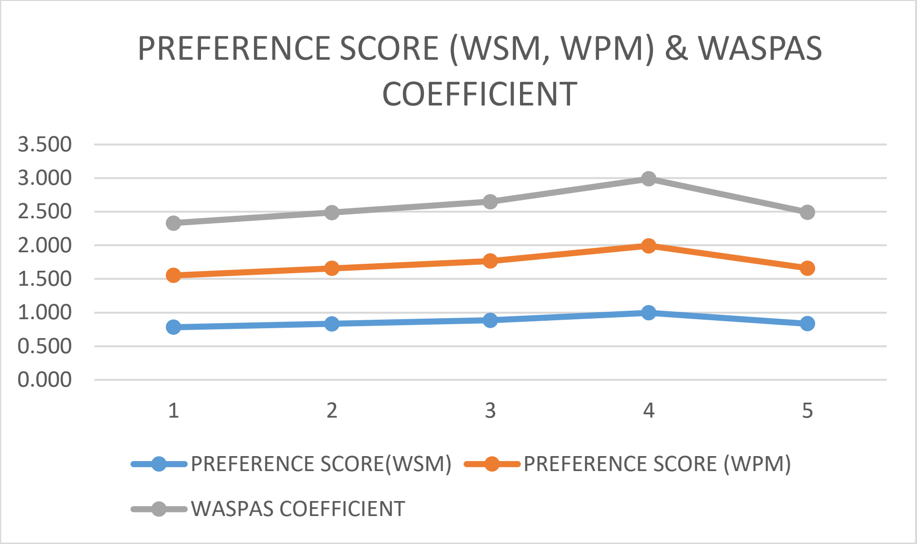

Figure 5. Preference Score (WSM, WPM) & WASPAS Coefficient

TABLE 7. Rank

WASPAS Coefficient	RANK
0.776	5
0.829	4
0.883	2
0.996	1
0.830	3

Table 7 shows the rank of alternative and evaluation parameters based on WASPAS Coefficient.

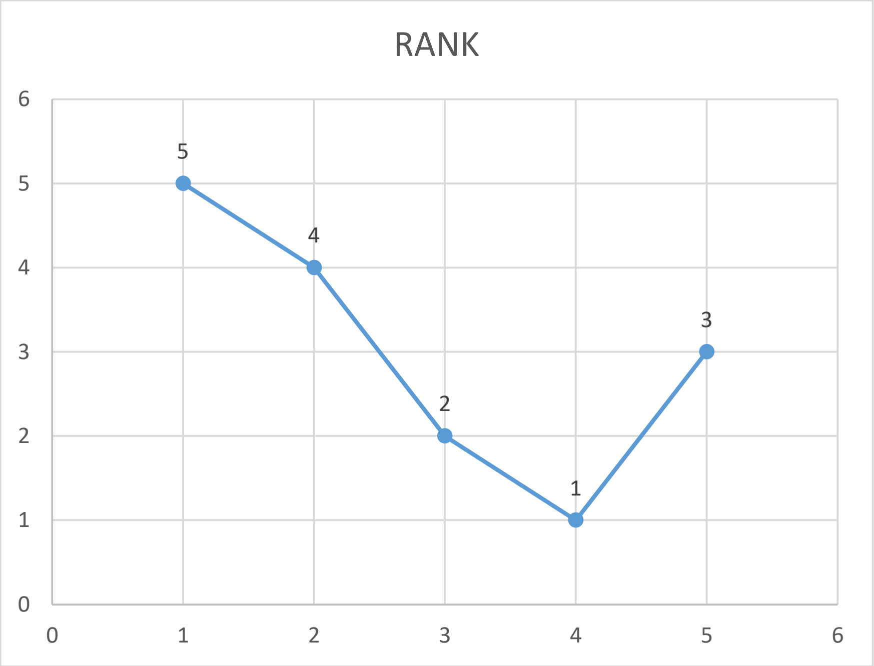

Figure 5 Rank

Figure 7 shows the rank of the data set LM-Alloy (+6 wt.% Porcelain, is on 1st rank, +4 wt.% Porcelain, is on 2nd rank, +8 wt.% Porcelain, is on 3rd rank, +2 wt.% Porcelain, is on 4th rank, +0 wt.% Porcelain, is on 5th rank).

4. CONCLUSION

In conclusion, Material selection for Automotive piston components is a critical decision in engine design, considering factors such as strength, heat resistance, wear resistance, weight, cost, and manufacturability. While the traditional choices of cast iron, aluminum alloys, and steel have their advantages and trade-offs, the integration of porcelain into LM alloys presents an interesting alternative. The addition of porcelain to LM alloys can enhance their mechanical properties, particularly in terms of wear resistance and thermal stability. By incorporating porcelain particles into the alloy matrix, the resulting composite material can exhibit improved hardness and reduced friction, leading to enhanced piston performance and longevity.

The qualities of the material are also greatly influenced by the weight proportion of porcelain in the LM alloy composition. Higher porcelain weight percentages can make a composite harder and more resistant to wear, but they can also make it more difficult to manufacture and machinate. Conversely, lower weight percentages of porcelain can help maintain the alloy's mach inability while still benefiting from some improvements in wear resistance. It is essential to strike a balance between the weight percentage of porcelain and other alloying elements to achieve the desired properties for piston components. This requires careful consideration of factors such as the specific engine application, operating conditions, and cost constraints. Overall, the integration of porcelain into LM alloys offers promising potential for enhancing the performance and durability of automotive piston components.

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