Jurnal Tribologi 49 (2026) 208-248

MYTRIBOS
Malaysian Tribology Society
Jurnal Tribologi
Website : jurnaltribologi.mytribos.org e-issn: 2289-7232
Jurnal Tribologi

The optimal eco-friendly lubricant selection using analytical hierarchy process

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KEYWORDS

Analytical hierarchy process
Castor oil
Jatropha oil
Mineral oil

ABSTRACT

The challenging process of selecting the best formulation of eco-friendly lubricant depends on various results and requires considering multiple parameters simultaneously. The analytical hierarchy process (AHP) is the most efficient formula in the multi-criteria decision analysis (MCDA) method for organizing and evaluating complex decisions. The study intends to determine the best eco-friendly lubricant using the AHP method via Expert Choice v.11.5 software. The AHP was used to rank the best candidate based on the experimental results provided. The selection process comprised three criteria, fifteen sub-criteria, and thirteen alternatives. AHP was performed with weighting and ranking. The consistency of judgement is measured utilizing the consistency ratio (CR) value, which must be less than 0.01. Sensitivity analysis was employed to validate the decision. S80C10J10 obtained the highest rank compared to other candidates with a priority value of 9.6%. The CR value is 0.00, and sensitivity analysis validated that S80C10J10 tops all three simulated scenarios with values of 9.9%, 9.7%, and 9.2%. S80C10J10 is the best formulation based on AHP analysis.

Received 27 April 2025; received in revised form 17 May 2025; accepted 20 May 2025.
To cite this article: Basiron et al. (2026). The optimal eco-friendly lubricant selection using analytical hierarchy process. Jurnal Tribologi 49, pp.208-248.

1.0 INTRODUCTION

Eco-friendly lubricants were developed using mineral oil SAE 15W40, castor oil, and jatropha oil as alternatives for reducing the usage of petroleum-based oil. All lubricants have undergone experimental physicochemical and tribological evaluations (Basiron and Abdollah, 2023; Basiron et al., 2023). However, the researcher had a difficult time selecting the best eco-friendly lubricant based on the results because several parameters had to be taken into consideration simultaneously, and each eco-friendly lubricant has a different set of results. The multi-criteria decision making (MCDM) or multi-criteria decision analysis (MCDA) method is one of the most exact methods for making decisions (Maklad et al., 2022; Taherdoost and Madanchian, 2023). The development of MCDM methods like the analytical hierarchy process (AHP) has enabled researchers to acquire the desired, optimal decision by employing a systematic, quantitative selection procedure (Ishak et al., 2019; Mansor et al., 2013). The AHP is a method for organizing and evaluating complex decisions in the theory of decision-making (Sharma, 2018). In order to analyse a problem, this method employs a hierarchical procedure, starting from the goal and moving down to criteria, sub-criteria, and alternatives at each consecutive level (Ali et al., 2023). In fact, it addresses difficult problems that involve simultaneously taking into consideration multiple criteria or alternatives (Aruldoss, 2013). Pair-wise comparisons of numerous options for various criteria are included in the AHP (Taherdoost and Madanchian, 2023). Utilizing AHP has advantages, including flexibility, intuitiveness, and checks for inconsistencies. In order to prevent bias in the decision-making process, the problem is arranged into a hierarchy that emphasizes the significance of each component (Aruldoss, 2013). Sensitivity analysis was employed to validate the decision. Sensitivity analysis is applied to determine how changing the weighting of one or more decision-making criteria affects the relative importance of the many alternatives (Aragonés-Beltrán et al., 2014). Performance, dynamic, gradient, and two-dimensional analysis are the four graphical sensitivity analysis modes that can be applied when applying AHP with Expert Choice v.11.5 software (Ahmad and Pirzada, 2014).

In previous research, decision-making was conducted using the AHP method (Ali et al., 2023; Ansah et al., 2015; Cay and Uyan, 2013; Liang and Chen, 2021; Safian and Nawawi, 2011), the AHP method with Expert Choice software (Abudeif et al., 2015; Ahmat et al., 2021; Erdogan et al., 2017; Firman et al., 2021; Hamidah et al., 2022; Yunus et al., 2013), and the AHP method with Expert Choice software and implemented sensitivity analysis (Ahmad and Pirzada, 2014; Ahmed Ali et al., 2015; Bagheri et al., 2021; Dweiri et al., 2016; Grabušic and Baric, 2022; Mansor et al., 2013; Razak et al., 2022). Expert Choice v.11.5 software has a graphic-based structure that allows it to apply judgement to goals and ultimately achieve the desired outcome (Yunus et al., 2013). Although their research is in a different field, it can nevertheless be utilized to support the methods or conclusions of this study.

Comparisons between the AHP-based land reallocation model and an interview-based land reallocation model revealed that 91.5% of participants were satisfied with the AHP-based model, whereas 62.7% were satisfied with the interview-based model (Cay and Uyan, 2013). According to the AHP method, the current state of the safety performance of the health, safety, and environment unit was not substantially affected by the COVID-19 pandemic, based on the calculations of the indicators and their assessments before and after the outbreak (Ali et al., 2023). In order to prioritise and create criterion weights for potential important plant areas (IPAs), the AHP approach, using Expert Choice software as a decision-making tool, revealed that threatened habitats receive the highest score, followed by threatened species, endemism and botanical richness (Hamidah et al., 2022). Using the AHP method and Expert Choice 11.5 software, the

Indonesian medical tourism business was chosen. The results showed that hospital accreditation and medical expertise/workforce were the most important elements for overall ranking (Firman et al., 2021).

The need to address the threats in coastal cities was determined using the AHP method with Expert Choice software, along with a sensitivity analysis. The findings of the study indicate that Zone 5 is particularly at risk and vulnerable (Bagheri et al., 2021). The ranking of the functional strategies (manufacturing, marketing, human resources, and financial management) utilised by the industry producing auto parts yields that the marketing strategy is regarded as the most important strategy, selected using the AHP method with Expert Choice software, along with a sensitivity analysis (Ahmad and Pirzada, 2014). The AHP results were validated by performing sensitivity analysis for four situations with a 20% increase in the priority vector, and it was found that blend 1 is the optimal blend (Razak et al., 2022). The results show that hemp and polypropylene had the highest ranking using various scenarios, with sensitivity analysis increased by 20% (Ahmed Ali et al., 2015). The AHP method selected that the best was kenaf bast fiber. As seen by the priority vector rising by 20% in the sensitivity analysis, kenaf bast fiber emerged as the best candidate material in two of the three simulated scenarios (Mansor et al., 2013). The suppliers are chosen and ranked based on sub-criteria via sensitivity analysis that suggests the effects of modifications in the main criteria on the ranking of suppliers (Dweiri et al., 2016). The three variations were suggested, and the results showed that variant 1 is the option with the highest rank for reconstruction based on a sensitivity analysis that makes sure the top-ranked choice is suitable (Grabušic and Baric, 2022). The AHP method, the AHP method with Expert Choice software, and the AHP method with Expert Choice software combined with implemented sensitivity analysis have been proven to be the most efficient for organizing and evaluating complex decisions.

The purpose of the study is to select the best eco-friendly lubricant using the AHP method with Expert Choice v.11.5 software and sensitivity analysis. The evaluation is conducted simultaneously based on numerous criteria and alternatives, representing a complex decision-making process. The AHP technique is quite beneficial for deciding among a lot of choices.

2.0 EXPERIMENTAL PROCEDURE

To achieve the purpose of the research, the study method was divided into two parts. The first phase was to carry out the experiment and calculation to gather the data, and the second was to utilize the AHP method and Expert Choice v.11.5 software to come to a choice based on the gathered data. First, eco-friendly lubricants were developed using mineral oil SAE 15W40, castor oil, and jatropha oil. All lubricant samples were subjected to six tribological performance evaluations and eight physicochemical tests. Six tribological performance measurements included friction, wear scar diameter (WSD), surface roughness, contact angle, lubricant film strength and thickness of the lubricant film. The lubricant film strength and the minimum film thickness were calculated using the Hamrock and Dowson formulae. The physicochemical tests included those for density, kinematic viscosity, viscosity index (VI), dynamic viscosity, flash point, total acid number (TAN), total base number (TBN) and water content.

Second, a decision was made based on the gathered data utilizing the AHP method and the Expert Choice v.11.5 software. The application of this software offers a crystal-clear picture of the choice and aids in making the best choice. The goal is to select the best candidate for the lubricant sample. The main criteria are wear analysis, surface characterization and physicochemical properties, with each main criterion consisting of parameters as sub-criteria (Figure 1). The alternatives consist of thirteen different types of lubricant samples, including three pure oils (S100, C100 and J100) and ten eco-friendly lubricants. Based on the testing results information gathered applying the pair-wise comparison technique developed by the AHP method, the alternatives were evaluated and ranked in terms of preference to one another. Using the priority vector values, the comparison data were later synthesized to determine the total score for the candidates. The consistency ratio values were calculated to evaluate the degree of consistency for the decisions taken in order to improve the precision and degree of confidence in the results. The best candidate for an eco-friendly lubricant was chosen using the Expert Choice v.11.5 software, which also carried out a sensitivity analysis to ensure that the choice was consistent.

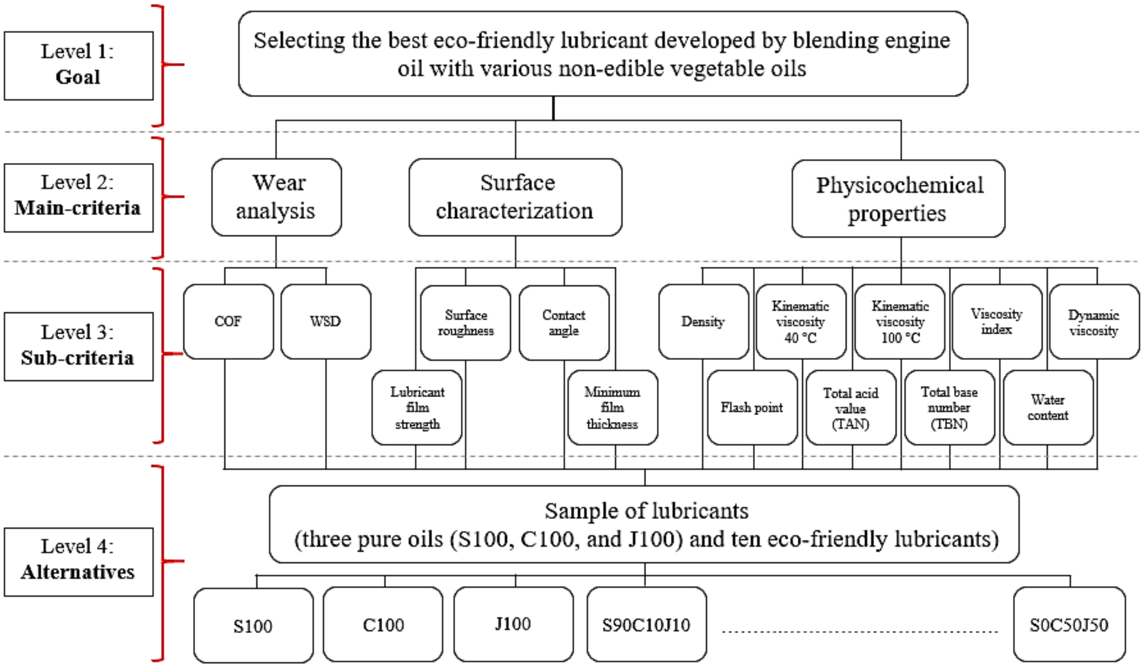


Figure 1: AHP hierarchy framework.

2.1 Experimental Methods

The experimental methods included detailed explanations of the development of eco-friendly lubricants, physicochemical tests, evaluation of tribological performance, and the numerous different mathematical equations that were employed to identify the component related to lubrication.

2.1.1 Lubricant sample preparation

The American Petroleum Institute (API) grade of SAE 15W40 is displayed in Table 1 (Performance and Oil, 2013). Vegetable oils extracted from plants include castor and jatropha. These three types of oils served as the foundational elements for the development of eco-friendly lubricants. Eco-friendly lubricants were developed utilising formulations in various volumetric concentrations, including varied ratios of 0 to 100 vol.% SAE 15W40 (S100), castor oil (C100) and jatropha oil (J100). Eco-friendly lubricants were created by blending substances with an ultrasonic homogenizer using the sonication technique. In this study, a 9 mm probe was used to sonicate the 300 mL of substances. The probe and beaker were thoroughly cleaned with hexane and acetone to remove any oil, dust, or dirt before S100 was inserted. The C100 and S100 were then merged for an hour. J100 was next added, and the mixture was continued for an additional hour. The identical two-hour technique was consumed to develop each of the ten eco-friendly lubricants (S90C5J5-S0C50J50), as shown in Table 2. The pure oils S100, C100, and J100 were used as control samples in this study.

Table1: API grade for SAE 15W40 (Performance & Oil, 2013).

Sample	**Parameter**		
	Properties	**Value**	**ASTM method**
SAE 15W40	Specific gravity at 15° C (g/mL)	0.876	D4052
	Flash point (°C)	232	D92
	Pour point (°C)	-27	D97
	Kinematic viscosity at 40 °C (mm^2/s)	109	D445
	Kinematic viscosity at 100 °C (mm^2/s)	15	D445
	Viscosity index (-)	143	D2270
	Total base number (mgKOH/g)	7.5	D2896
	Color (-)	<3.0	D1500

Table 2: Information regarding the lubricant samples.

Sample	**Concentration of volume percentage**		
	SAE 15W40 (%)	**Castor oil (%)**	**Jatropha oil (%)**
S100	100	0	0
C100	0	100	0
J100	0	0	100
S90C5J5	90	5	5
S80C10J10	80	10	10
S70C15J15	70	15	15
S60C20J20	60	20	20
S50C25J25	50	25	25
S40C30J30	40	30	30
S30C35J35	30	35	35
S20C40J40	20	40	40
S10C45J45	10	45	45
S0C50J50	0	50	50

2.1.2 Physicochemical properties tests

The definition of density is the mass of a substance per unit volume (Hiteshwer et al., 2018). The density of the lubricant samples was established through measurements using a hydrometer. Each sample of lubricant to be tested was placed in a graduated cylinder containing 100 mL, and the hydrometer was then slowly lowered into the liquid until it floated freely. The reading from the hydrometer in accordance with the ASTM D1298-12b standard test technique is utilized for density, relative density, or API gravity of crude oil and liquid petroleum products since it expresses that precise assurance of the API gravity (Hiteshwer et al., 2018). The accompanying Equation 1 shows the numerical relationship between density, mass, and volume as follows:

$$\rho = \frac{m}{V} \tag{1}$$

where ρ (kgm^{-3}) is density, m (kg) is mass, and V (m^3) is volume (Hiteshwer et al., 2018).

The kinematic viscosity of lubricant samples was measured at 40 °C and 100 °C utilizing the HK265A kinematic viscosity apparatus, which complies with ASTM D445. The capillary viscometer for the kinematic viscometer equipment was an Ubbelohde viscometer in size 1C (0.78 mm). The ratio of dynamic viscosity to fluid density is known as kinematic viscosity (Quinchia et al., 2014). The VI was calculated using the results of the kinematic viscosity. The ASTM D2270 recommended method was used to calculate the VI of lubricant samples. As seen below, the kinematic viscosity is calculated using Equation 2 (Torbacke et al., 2014).

$$\mu = \frac{\eta}{\rho} \tag{2}$$

where μ (mm^{2}s^{-1}) is kinematic viscosity, η (Pas) is dynamic viscosity and ρ (kgm^{-3}) is fluid density (Torbacke et al., 2014).

The flash point of lubricant samples was determined by employing the Seta flash point tester in accordance with ASTM D3828 recommendations. Use an o-ring seal in the color red for temperatures more than 110 °C. It is necessary to inject the sample into the filler orifice, which is 2 mL for anticipated flash points up to and including 100 °C and 4 mL above 100 °C. Seta flash small-scale closed cup tester uses a 2 mL or 4 mL sample to quickly achieve equilibrium between the vapor and the liquid in a cup and provides a reliable flash point result in just one or two minutes (Hshieh and Hshieh, 2005). The timer button to start a countdown that lasts from 60 s to 0 s.

The 848 titrino plus titrator enables the TAN to be determined using standard methods in compliance with the recognized American (ASTM D664) standard (Santos et al., 2018). The titration solvent was prepared utilizing toluene, isopropanol (IPA) and distilled water in portions of 500 mL, 495 mL, and 5 mL, respectively (ASTM International, 2018). 40 mL of isopropanol, 20 mL of distilled water, and 0.06 g of potassium hydroxide made up the chemical titrant. Utilizing a few drops of chemical titrant mixed with 120 mL of the titration solvent, a blank determination was first made until the reading was less than 0.1 mL. The blank determination reading of less than 0.1 mL displayed that the mix was permitted to proceed to the next stage of the process. 120 mL of titration solvent and 5 g of lubricant sample were combined for the TAN measurement. The mixture was titrated until the equivalency point was attained using a chemical titrant. The reading was captured by the display. The electrode needs to be rinsed with solvent solution, followed by IPA, and then rehydrated with deionized water after each sample determination (Santos et al., 2018). The remaining water was immediately removed from the electrode by immersing it in IPA (T. A. N. and Note, 2020).

The TBN of samples was calculated utilizing the 848 titrino plus titrator in accordance with ASTM D2896. The ASTM D2896 method is the recognized method for determining TBN in fresh and used oils (Wolak, 2018). The titration solvent was made using glacial acetic acid and chlorobenzene in a ratio of 1:2 (500 mL:1000 mL). The chemical titrant contained only perchloric acid (D2896-03, 2003). In order to perform a blank determination, 120 mL of the titration solvent was mixed with a few drops of chemical titrate until the equivalency point was reached and a reading of less than 0.1 mL was obtained. Based on the blank determination reading of less than 0.1 mL, the mix was allowed to continue to the next step of the process. The TBN measurement was performed employing a combination of 5 g of lubricant sample and 120 mL of titration solvent. Prior to reaching the equivalency point, the mixture was titrated deploying a chemical titrant. The screen stored the reading. After the titration was completed, clean the electrodes with the titration solvent to remove any adhering oily residue left over from the prior titration. The electrodes must first be cleaned with water before being rinsed with the titration solvent.

Karl Fischer suggested employing the 899 coulometers as a titrator to determine the coulometric water content (Lanz et al., 2006). The testing of coulometric Karl Fischer titrators in accordance with GLP/ISO 9001 (Metrohm, 2015). Hydranal Coulomat AG (methanol-based) was used as a reagent or an anolyte for coulometric Karl Fischer titration (Lanz et al., 2006; Metrohm, 2015). 100 mL of reagent should be poured into the coulometer cell using a funnel. In order to titrate as many samples as feasible in the same reagent solution and to shorten the titration time, the sample weight should be minimal (5 g). The lubricant sample was injected into the vessel through the septum using a long needle. The generator electrode, indicator electrode, and glass vessel should all be cleaned with a solvent such as chloroform or toluene. Vessel and double Pt electrode can be washed with detergent and water.

2.1.3 Four-ball wear test

In accordance with the recommended ASTM D4172-94 methods, the antifriction and anti-wear qualities of oil were evaluated using a Ducom Instruments® four-ball tribometer (Abdollah et al., 2020; D4172, 1999). The following parameters were selected for this test: 1200 rpm, 392.4 N, 3600 s and 75 °C, respectively. The main components of the instrument are the ball-pot assembly, collet with locknut, and standard steel ball bearings. As shown in Table 3, the ball bearing utilized in these tests, which was made of carbon-chromium steel (AISI 52100), had a diameter of 12.7 mm and was suitable for bearing applications. Four new ball bearings were utilized for every test. All ball bearings were cleaned before testing by soaking in acetone for 15 minutes in an ultrasonic cleaner, followed by a period of drying in the absence of moisture. The lubricant sample was filled to the ball pot in an amount of around 10 mL, (Jamaluddin et al., 2020) at least 3 mm above the three ball bearings for every test (Sharma and Sachan, 2019). The schematic diagram of the ball port assembly is displayed in Figure 2. The fourth ball bearing was fixed in the spindle using a steel collet, and an AC motor was applied to revolve it. The frictional torque was measured using Winducom 2010 software, which was connected to the four-ball tribometer.

Table 3: The mechanical properties of the ball bearing.

Sample	**Parameter**		
Ball bearing	**Hardness (HRC)**	**Density (g/cm^3)**	**Surface roughness *Ra* (μm)**
	61	7.79	0.022

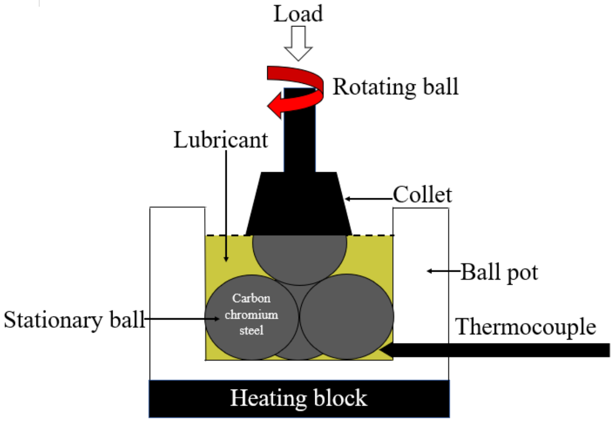


Figure 2: Schematic diagram of ball pot assembly.

2.1.4 Friction evaluation

A beam-type load cell was used to measure the frictional torque. The load cell was located around 80 mm from the centre of the spindle. The friction force between two bodies and the normal force forcing them together is expressed as a dimensionless number called the coefficient of friction (COF). COF is a critical factor in determining the transmission efficiency under lubricated conditions; a lower COF indicates less friction, which adds to better efficiency (Zulkifli et al., 2014). The COF calculated for these tests using ASTM D4172 standards is depicted in Equation 3 below:

$$\mu = \frac{T\sqrt{6}}{3Wr} \tag{3}$$

where μ is the COF, T (Nm) is the frictional force, W (N) is applied load, and r (m) is the 3.67 mm distance measured between the axis of rotation and the centre of the contact surface on the lower ball bearings (Jabal et al., 2019).

2.1.5 Surface characterization

Scanning electron microscopy (SEM) was used to evaluate the surface morphology of the worn surfaces, and energy dispersive X-ray (EDX) spectroscopy was utilized to determine the chemical composition (Abdollah et al., 2020). The wear rate on the ball bearing surface was determined by measuring the diameter of the wear scar made by the upper ball bearing rubbing on three stationary steel ball bearings. The surface roughness *Ra* of the three stationary steel ball bearings was measured by applying a roughness measure both transversely and along the rubbing direction. The WSD and surface roughness of the worn material were measured by employing a profilometer. The profilometer was comprised of a digital microscope connected to a computer running either the WindROOF 2015 measurement program or image processing software (Abdollah et al., 2020). Initially, a stage with a ball bearing beneath a camera lens and a light switch was lit. Glance to the side and lightly touch the ball bearing scar. Employ only the fine focus. In order to get a clean image, adjust the diaphragm. Once the image appears to be clear, the WSD image was captured so that the surface roughness may be measured. The diameter of the wear scar and surface roughness were then determined by averaging the collected data.

The degree of wetting of the lubricant sample will be indicated by the contact angle. The static contact angle of the lubricant sample was measured using a contact angle measurement tool, which also determined the surface wettability. As a part of the wettability investigation, the contact angle between the lubricants and the polished, smooth steel plates made from carbon steel was calculated. The polished carbon chromium steel plate has a surface roughness *Ra* of 0.35 µm. A droplet of 5 µL lubricant sample (Allred et al., 2019) was positioned on the edge of a smooth steel plate. The steel plate was placed in front of and closest to a computer-connected digital microscope. This is the place where the image was taken. The lubricant sample droplet was viewed and imaged through a digital viewer. Using lubricant sample droplets positioned at various points along the edge of the stage, the process was repeated four times. The contact angle was calculated by analyzing each image of a lubricant sample droplet using the measurement tool ImageJ. The average of the contact angles for each of the four locations can be utilized to determine the contact angle.

2.1.6 Lubricant film strength and maximum contact pressure

Three stationary balls in the cup were covered with a small layer of lubricant to allow for direct contact with the higher rotating ball. Film strength is the capacity of lubricants to lessen wear and the effects of friction (Hamrock et al., 2004). The lubricant film strength can be determined by applying Equation 4.

$$L_S = \frac{4}{\pi(WSD)^2} x \frac{\sqrt{6}}{6} F \tag{4}$$

where L_s (Pa) is lubricant film strength, F (N) is load, and WSD (m) is wear scar diameter (Abdollah et al., 2021).

The centre of the contact patch displays the maximum pressure. The maximum contact pressure is calculated using the Hertz contact theory by Equation 5 (Asbeck et al., 2006) as illustrated below.

$$P_{max} = \left[\frac{6FE^{*2}}{\pi^3 R^2}\right]^{\frac{1}{3}} \tag{5}$$

where P_{max} (Pa) is maximum contact pressure, F (N) is load, E^* (Pa) = $\frac{E}{2(1-\mu^2)}$ is effective Young's modulus, E (Pa) is Young's modulus of the ball bearing (210 GPa), μ is Poisson's ratio of the ball bearing (0.3), and R (m) is the radius of a ball bearing (0.00635 m)(Asbeck et al., 2006).

2.2 Analytical Hierarchy Process Methods

Figure 3 outlines the ten steps to select the best eco-friendly lubricant using the AHP methods and Expert Choice v.11.5 software. The subheading section provided a detailed explanation of applying AHP methods with Expert Choice v.11.5 software, leading to the generated results.

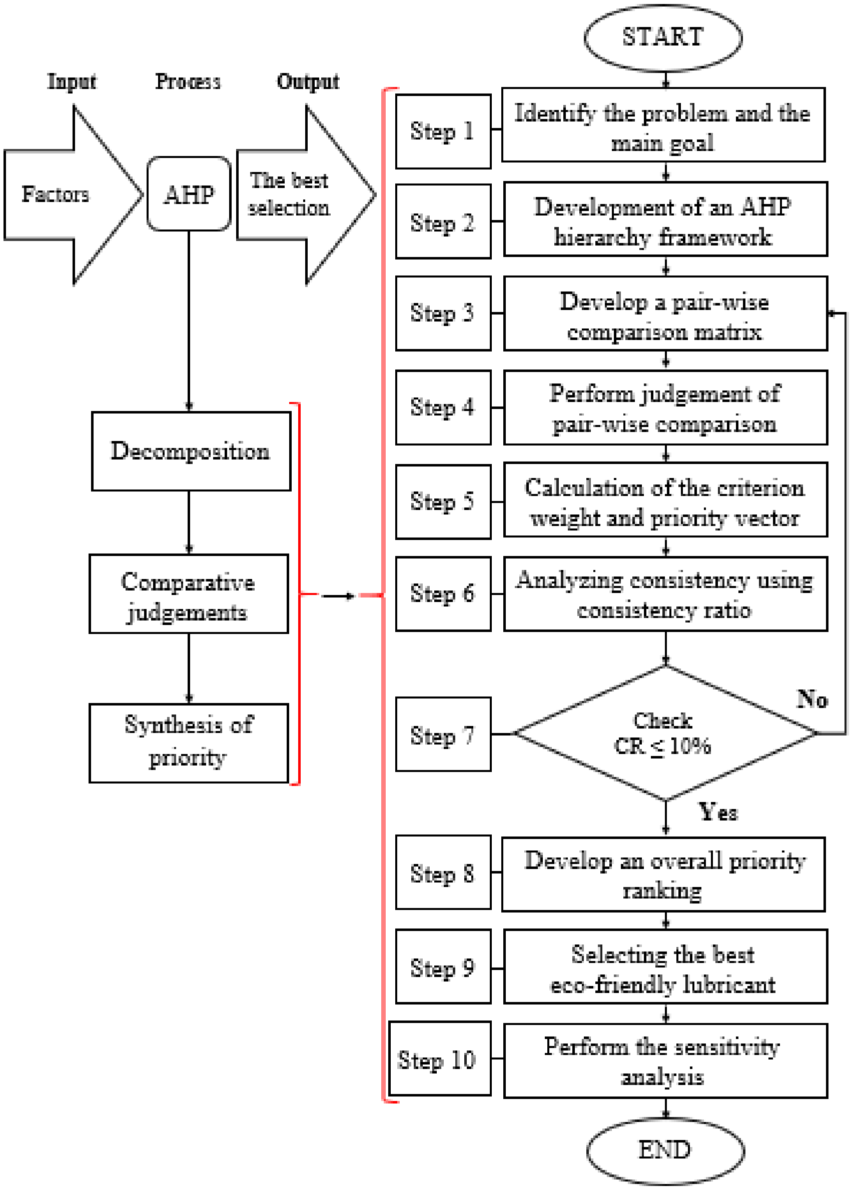


Figure 3: Flowchart outlining the ten steps to choose the best eco-friendly lubricant.

2.2.1 Step 1: Identify the problem and main goal

Prior to determining the main goal, an initial investigation should be carried out to precisely determine the main problem (Ali et al., 2015). The main problem was that the researcher faced several difficulties in choosing the best eco-friendly lubricant based on the experimental results obtained since many variables needed to be taken into consideration simultaneously. Additionally, it can be difficult to choose the best eco-friendly lubricant candidates because each lubricant has a distinctive set of results. The main goal was to select the best eco-friendly lubricant.

2.2.2 Step 2: Development of an analytical hierarchy process framework

There are two steps involved in developing an AHP framework. The first step is to identify the levels of the AHP framework; the second step is to decide the main goal, the criteria, the sub-criteria, and the alternatives. The first step is the AHP hierarchy framework, which is depicted in Figure 4. As seen in Figure 4, the model was presented with four levels in this study: level 1 is the objective or goal of the study, level 2 describes the main criteria or parameters that determine the goal, level 3 includes the sub-criteria or also the parameters, and level 4 is the bottom level and displays the set of alternatives (candidates for the lubricant samples). Every parameter was interconnected, using connecting lines to illustrate their relationships within the hierarchy framework.

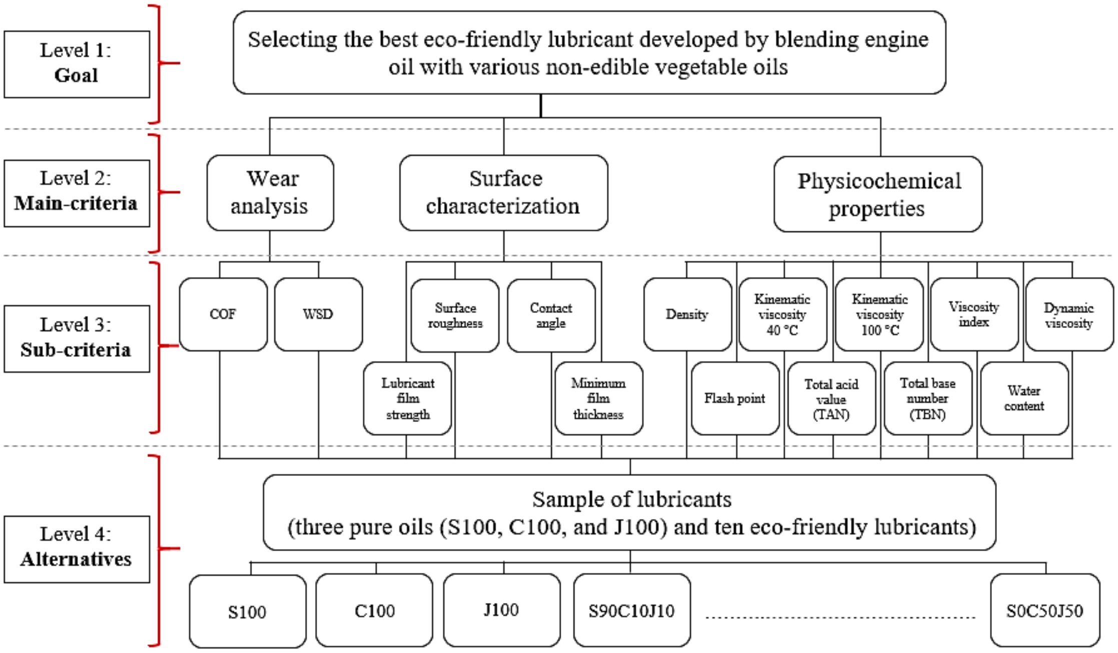
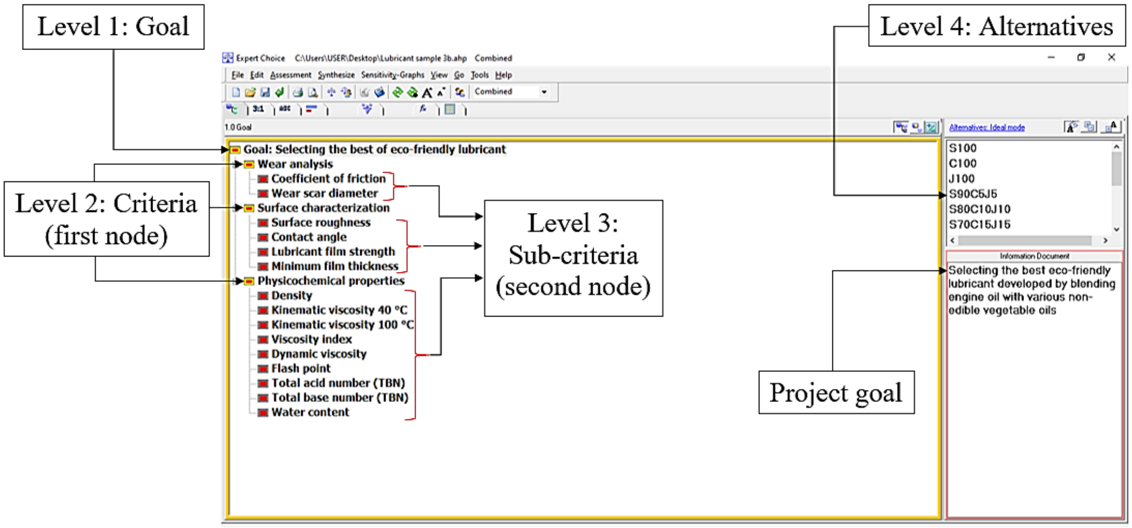


Figure 4: Development of analytical hierarchy process framework for selecting the best eco-friendly lubricant.

The main goal, main criteria, sub-criteria, and alternatives are all explained in the second step. The project goal was to select the best eco-friendly lubricant. The main criteria comprised wear analysis, surface characterization, and physicochemical properties. The sub-criteria included COF, WSD, surface roughness, contact angle, lubricant film strength, minimum film thickness, density, kinematic viscosity, VI, dynamic viscosity, flash point, TAN, TBN, and water content. The alternatives consisted of thirteen lubricant samples, including ten eco-friendly lubricants and three pure oils (S100, C100 and J100). Thus, the first level of the hierarchy framework describes the goal; the second level has three criteria (first node); the third level has fifteen sub-criteria (second node); the fourth level has thirteen alternatives. Table 4 is provided to facilitate the use of the Expert Choice v.11.5 software. In order to select the best eco-friendly lubricants, all pertinent parameters listed in Table 4 were entered into the Expert Choice software, as shown in Figure 5.

Table 4: An overview of the hierarchy framework in selecting the best eco-friendly lubricant.

Specification	**Parameter**			
	Level-1	**Level-2**	**Level-3**	**Level-4**
	Goal	**Criteria (first node)**	**Sub-criteria (second node)**	**Alternatives**
AHP framework	To select the best eco-friendly lubricant	Wear analysis	COF	S100 - S0C50J50
			WSD	S100 - S0C50J50
		Surface characterization	Surface roughness *Ra*	S100 - S0C50J50
			Contact angle	S100 - S0C50J50
			Lubricant film strength	S100 - S0C50J50
			Minimum film thickness	S100 - S0C50J50
		Physicochemical properties	Density	S100 - S0C50J50
			Kinematic viscosity 40 °C	S100 - S0C50J50
			Kinematic viscosity 100 °C	S100 - S0C50J50
			Viscosity index	S100 - S0C50J50
			Dynamic viscosity	S100 - S0C50J50
			Flash point	S100 - S0C50J50
			TAN	S100 - S0C50J50
			TBN	S100 - S0C50J50
			Water content	S100 - S0C50J50



Goal: Selecting the best of eco-friendly lubricant
- Wear analysis
  - Coefficient of friction
  - Wear scar diameter
- Surface characterization
  - Surface roughness
  - Contact angle
  - Lubricant film strength
  - Minimum film thickness
- Physicochemical properties
  - Density
  - Kinematic viscosity 40 °C
  - Kinematic viscosity 100 °C
  - Viscosity index
  - Dynamic viscosity
  - Flash point
  - Total acid number (TBN)
  - Total base number (TBN)
  - Water content

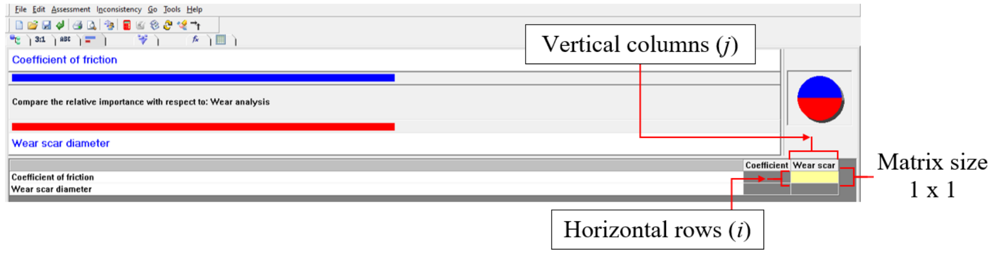
S100
C100
J100
S90C5J5
S80C10J10
S70C15J15

Selecting the best eco-friendly lubricant developed by blending engine oil with various non-edible vegetable oils

Figure 5: The Expert Choice software window for analytical hierarchy process framework.

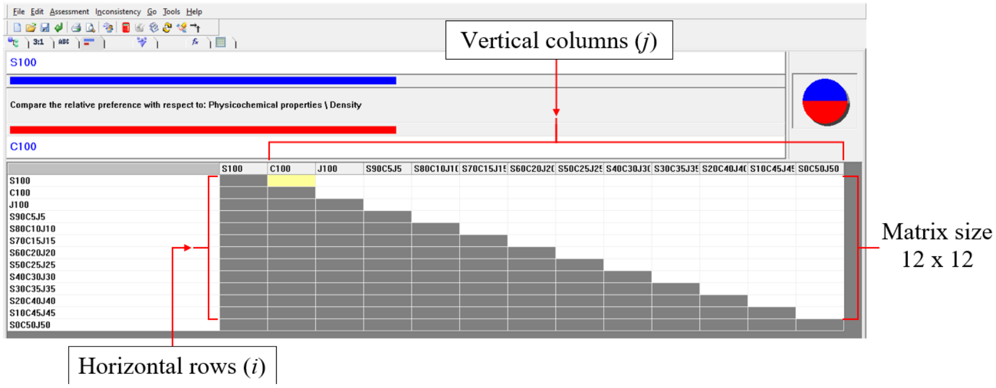
2.2.3 Step 3: Development a pair-wise comparison matrix

A square matrix of order *n x n* acted as the pair-wise comparison matrix (Ali et al., 2015). The number of children (criteria or alternatives) being compared in relation to a particular parent (goal) determines the size of the comparison matrix, which has dimensions of *n x n* (Dweiri et al., 2016). Horizontal rows (*i*) and vertical columns (*j*) form a matrix with *i x j* elements, represented by the notation a_{ij}. Figure 6 shows an example of how to develop a pair-wise comparison matrix using Expert Choice v.11.5 software.



Compare the relative importance with respect to: Wear analysis

(a) Pair-wise matrix for the first node.



Compare the relative preference with respect to: Physicochemical properties \ Density

(b) Pair-wise matrix for the second node.

Figure 6: The development of a pair-wise comparison matrix.

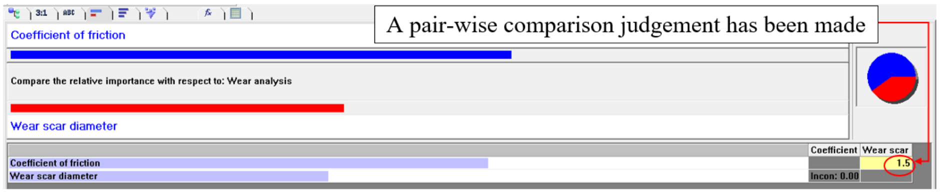
Based on the number of criteria employed in the hierarchy framework, the number of pair-wise comparison assessments is determined via the Equation 6 rule:

$$Number\ of\ pair-wise\ comparison = n(n-1) \qquad (6)$$

where *n* is the total number of criteria (Ali et al., 2015; Mansor et al., 2013).

2.2.4 Step 4: Perform judgement of pair-wise comparison

A pair-wise comparison judgement is a technique that compares two entities to establish which is preferred, possesses a higher quantity, or if the two are identical (Ali et al., 2015). Pairwise comparison is a numerical ranking process. All data in this study (main criteria and sub-criteria) were used in performing a pair-wise comparison judgement. Each node in the hierarchy compiles its pair-wise comparison judgement into a matrix as demonstrated in Figure 7.

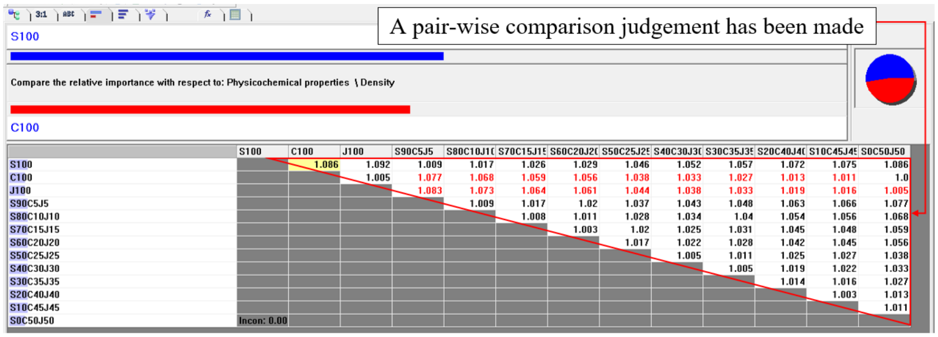


A pair-wise comparison judgement has been made

Compare the relative importance with respect to: Wear analysis

	Coefficient	Wear scar
Coefficient of friction		1.5
Wear scar diameter	Incon: 0.00	

(a) A pair-wise comparison judgement for the first node.



A pair-wise comparison judgement has been made

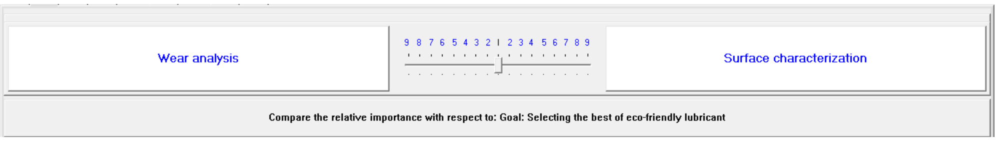
Compare the relative importance with respect to: Physicochemical properties \ Density

	S100	C100	J100	S90C5J5	S80C10J1	S70C15J1	S60C20J2	S50C25J2	S40C30J3	S30C35J3	S20C40J4	S10C45J4	S0C50J50
S100		1.086	1.092	1.009	1.017	1.026	1.029	1.046	1.052	1.057	1.072	1.075	1.086
C100			1.005	1.077	1.068	1.059	1.056	1.038	1.033	1.027	1.013	1.011	1.0
J100				1.083	1.073	1.064	1.061	1.044	1.038	1.033	1.019	1.016	1.005
S90C5J5					1.009	1.017	1.02	1.037	1.043	1.048	1.063	1.066	1.077
S80C10J10						1.008	1.011	1.028	1.034	1.04	1.054	1.056	1.068
S70C15J15							1.003	1.02	1.025	1.031	1.045	1.048	1.059
S60C20J20								1.017	1.022	1.028	1.042	1.045	1.056
S50C25J25									1.005	1.011	1.025	1.027	1.038
S40C30J30										1.005	1.019	1.022	1.033
S30C35J35											1.014	1.016	1.027
S20C40J40												1.003	1.013
S10C45J45													1.011
S0C50J50	Incon: 0.00												

(b) A pair-wise comparison judgement for the second node.

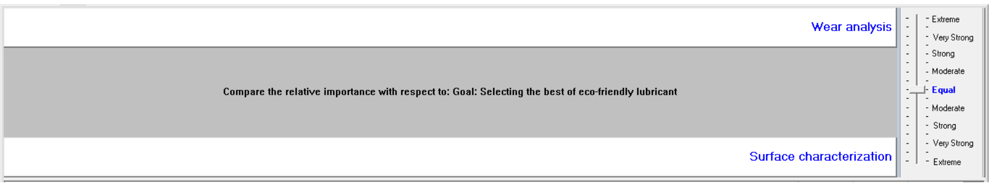
Figure 7: The judgement of the pair-wise comparison matrix.

The ability to compare criteria and alternatives using the nine-level preference scale is one benefit of AHP (Ishizaka and Labib, 2009). The nine-level preference scale can be represented in verbal, graphical, and numerical forms (Ishizaka and Labib, 2009). These scales are displayed in the Expert Choice v.11.5 software window, as seen in Figure 8. The graphic scales were used as judgement scales in this study.



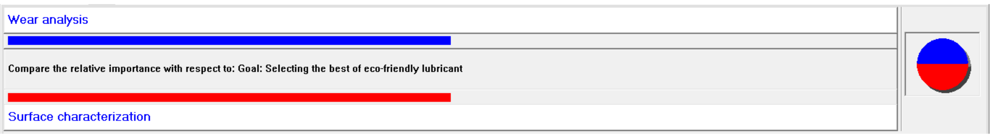
Compare the relative importance with respect to: Goal: Selecting the best of eco-friendly lubricant

(a) Numerical scale.



Compare the relative importance with respect to: Goal: Selecting the best of eco-friendly lubricant

(b) Verbal scale.



Compare the relative importance with respect to: Goal: Selecting the best of eco-friendly lubricant

(c) Graphical scale.

Figure 8: The type of rating scale.

Table 5: The basic analytical hierarchy process importance scale (Ahmad and Pirzada, 2014; Ali et al., 2015; Bagheri et al., 2021; Dweiri et al., 2016; Grabušic and Baric, 2022; Maklad et al., 2022; Mansor et al., 2013).

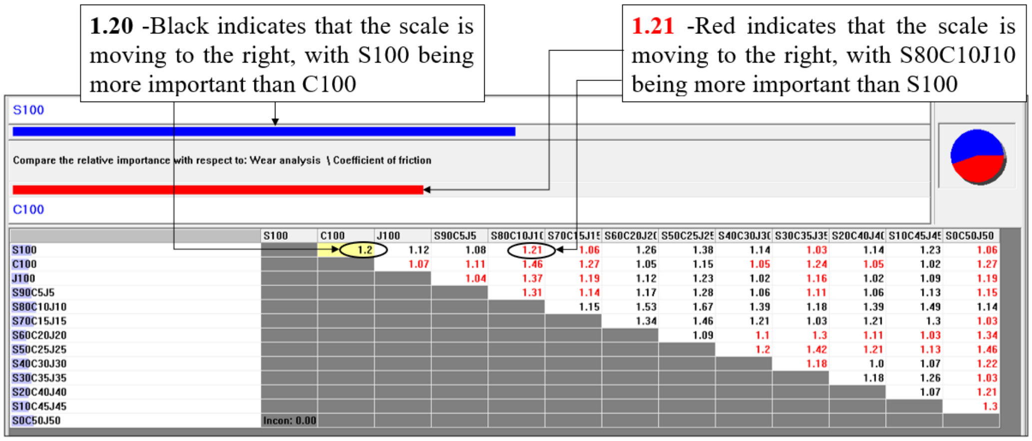
The Saaty scale	**Parameters**	
The intensity is an important numerical scale	**Definition of importance scale**	**Note**
1	Both parameters are equally important	* For any pair matrix with components *i* x *j* * If the judgement value is on the left, the actual judgement value is taken, and if it is on the right, the reciprocal value is taken
3	Judgement places a little bit more importance on one parameter than another	
5	One parameter has priority over another while judgement is essential or highly important	
7	Very high importance of one parameter compared to another	
9	Extreme importance of one parameter compared to another parameter	
2, 4, 6, 8	A set of values that fall between the two adjacent judgements	
Reciprocals	Reciprocal comparisons for the inverse	

Table 6: Example of calculating the pair-wise comparison ratio of the alternative with regard to the coefficient of friction.

Main criteria	**Sub-criteria**	**Alternatives**	**Comparison ratio**	**Reverse comparison**
Wear analysis	COF - 0.0918	S100	S100 : C100 0.0918 : 0.1102 $\frac{0.0918}{0.1102} = 0.833 < 1$	C100 : S100 0.1102 : 0.0918 $\frac{0.1102}{0.0918} = 1.20$
	COF - 0.1102	C100		
	COF - 0.0918	S100	S100 : S80C10J10 0.0918 : 0.0756 $\frac{0.0918}{0.0756} = 1.214$	-
	COF - 0.0756	S80C10J10		

A Saaty formed numerical scale ranging from 1 to 9 to compare one criterion to another and assess the scores (Hamidah et al., 2022). Table 5 displays the rating scale for pair-wise comparison utilized in this study (Ahmad and Pirzada, 2014; Ali et al., 2015; Bagheri et al., 2021; Dweiri et al., 2016; Grabušic and Baric, 2022; Maklad et al., 2022; Mansor et al., 2013). If two elements are equally important, a score of 1 is given to indicate equality; if an element receives a score of 9, it indicates that it is significantly more important than the other element (Ahmad and Pirzada, 2014). Each pair-wise comparison also makes use of reciprocals (Ahmad and Pirzada, 2014). The rating scale would be 9 if it were assumed that criterion *X* was unquestionably more important than criterion *Y*; conversely, the rating scale value of 1/9 indicates that *Y* must be considerably more important than *X* (Ali et al., 2015). It is necessary to perform the calculation in reverse since the given value cannot be less than 1 (Ali et al., 2015).

To simplify the process of calculating pair-wise comparison ratios based on the Saaty scale, Table 6 provides example calculations for alternatives regarding COF. Additionally, Figure 9, derived from Table 6, displays a pair-wise comparison ratio for the alternatives regarding COF, generated using Expert Choice v.11.5 software.



1.20 -Black indicates that the scale is moving to the right, with S100 being more important than C100

1.21 -Red indicates that the scale is moving to the right, with S80C10J10 being more important than S100

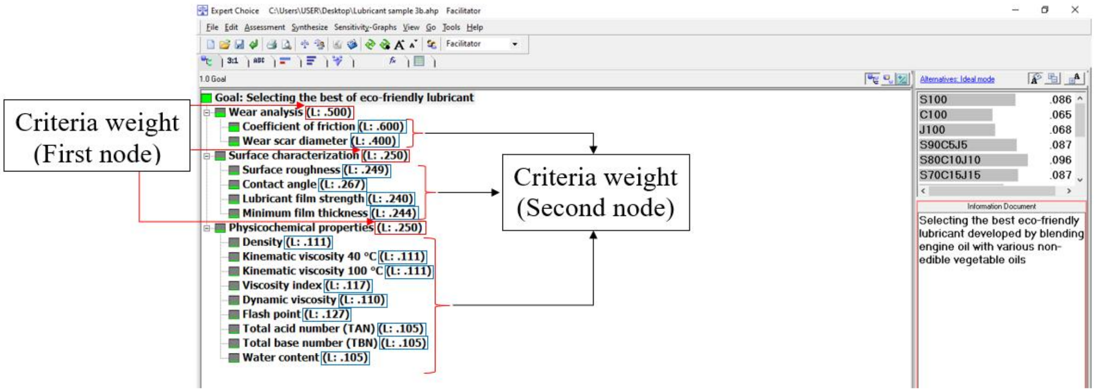
Compare the relative importance with respect to: Wear analysis \ Coefficient of friction

	S100	C100	J100	S90C5J5	S80C10J1	S70C15J1	S60C20J2	S50C25J2	S40C30J3	S30C35J3	S20C40J4	S10C45J4	S0C50J50
S100		1.2	1.12	1.08	1.21	1.06	1.26	1.38	1.14	1.03	1.14	1.23	1.06
C100			1.07	1.11	1.46	1.27	1.05	1.15	1.05	1.24	1.05	1.02	1.27
J100				1.04	1.37	1.19	1.12	1.23	1.02	1.16	1.02	1.09	1.19
S90C5J5					1.31	1.14	1.17	1.28	1.06	1.11	1.06	1.13	1.15
S80C10J10						1.15	1.53	1.67	1.39	1.18	1.39	1.49	1.14
S70C15J15							1.34	1.46	1.21	1.03	1.21	1.3	1.03
S60C20J20								1.09	1.1	1.3	1.11	1.03	1.34
S50C25J25									1.2	1.42	1.21	1.13	1.46
S40C30J30										1.18	1.0	1.07	1.22
S30C35J35											1.18	1.26	1.03
S20C40J40												1.07	1.21
S10C45J45													1.3
S0C50J50	Incon: 0.00												

Figure 9: Pair-wise comparison ratios of the alternative with regard to coefficient of friction.

2.2.5 Step 5: Calculation of the criterion weight and priority vector (Eigenvector)

A weight is a numerical value that represents the importance of an assessment criterion in respect to other criteria (Abudeif et al., 2015). The larger weight indicates that criteria play a more important role in the overall utility (Abudeif et al., 2015). A pairwise comparison judgement method is helpful in determining the weighted ranking of criteria, sub-criteria, and alternatives. A pairwise comparison judgement is first implemented on the first node to determine the criteria weight. The criteria weight of the second node is automatically generated after the pairwise comparison judgement on the first node is completed. Figure 10 shows the criteria weight for the first node and the second node on the Expert Choice window.



Criteria weight (First node)

Criteria weight (Second node)

Goal: Selecting the best of eco-friendly lubricant
- Wear analysis (L: .500)
  - Coefficient of friction (L: .600)
  - Wear scar diameter (L: .400)
- Surface characterization (L: .250)
  - Surface roughness (L: .249)
  - Contact angle (L: .267)
  - Lubricant film strength (L: .240)
  - Minimum film thickness (L: .244)
- Physicochemical properties (L: .250)
  - Density (L: .111)
  - Kinematic viscosity 40 °C (L: .111)
  - Kinematic viscosity 100 °C (L: .111)
  - Viscosity index (L: .117)
  - Dynamic viscosity (L: .110)
  - Flash point (L: .127)
  - Total acid number (TAN) (L: .105)
  - Total base number (TBN) (L: .105)
  - Water content (L: .105)

S100	.086
C100	.065
J100	.068
S90C5J5	.087
S80C10J10	.096
S70C15J15	.087

Selecting the best eco-friendly lubricant developed by blending engine oil with various non-edible vegetable oils

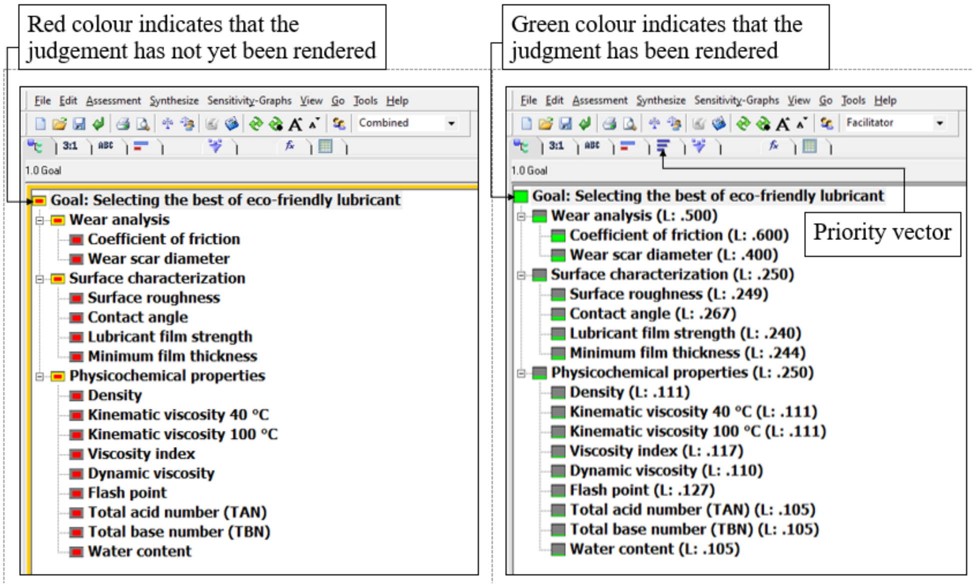
Figure 10: Criterion weight.

The priority vector (eigenvector) can be found using the following Equation 7:

$$W = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{ij}}{\sum_{i=1}^{a} a_{ij}} \tag{7}$$

where i and j are equivalent in 1, 2, 3, 4, ..., n, W is the priority vector (eigenvector), a_{ij} is an important Saaty scale (consulted Table 5), and n is the number of the criteria (Ali et al., 2015; Mansor et al., 2014).

However, the AHP uses a pairwise comparison matrix to create a priority vector, determining the relative importance of criteria or alternatives. The priority vector is indicated in blue once the pairwise comparison judgements for all nodes have been fully evaluated, as illustrated in Figure 11.


Red colour indicates that the judgement has not yet been rendered

Green colour indicates that the judgment has been rendered

Priority vector

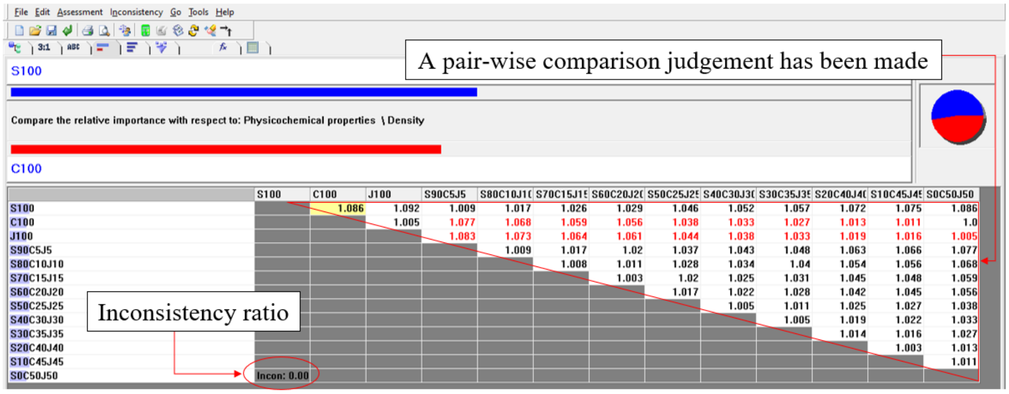
- 🟥 Goal: Selecting the best of eco-friendly lubricant
  - 🟥 Wear analysis
    - 🟥 Coefficient of friction
    - 🟥 Wear scar diameter
  - 🟥 Surface characterization
    - 🟥 Surface roughness
    - 🟥 Contact angle
    - 🟥 Lubricant film strength
    - 🟥 Minimum film thickness
  - 🟥 Physicochemical properties
    - 🟥 Density
    - 🟥 Kinematic viscosity 40 °C
    - 🟥 Kinematic viscosity 100 °C
    - 🟥 Viscosity index
    - 🟥 Dynamic viscosity
    - 🟥 Flash point
    - 🟥 Total acid number (TAN)
    - 🟥 Total base number (TBN)
    - 🟥 Water content

- 🟩 Goal: Selecting the best of eco-friendly lubricant
  - 🟩 Wear analysis (L: .500)
    - 🟩 Coefficient of friction (L: .600)
    - 🟩 Wear scar diameter (L: .400)
  - Surface characterization (L: .250)
    - Surface roughness (L: .249)
    - Contact angle (L: .267)
    - Lubricant film strength (L: .240)
    - Minimum film thickness (L: .244)
  - Physicochemical properties (L: .250)
    - Density (L: .111)
    - Kinematic viscosity 40 °C (L: .111)
    - Kinematic viscosity 100 °C (L: .111)
    - Viscosity index (L: .117)
    - Dynamic viscosity (L: .110)
    - Flash point (L: .127)
    - Total acid number (TAN) (L: .105)
    - Total base number (TBN) (L: .105)
    - Water content (L: .105)

Figure 11: The priority vector.

2.2.6 Step 6: Analysing consistency using consistency ratio

Measures of consistency in AHP include the inconsistency ratio and consistency ratio (CR). When the pair-wise judgments are arranged in a linear order based on their importance, the pair-wise comparison matrix becomes inconsistent. Inconsistency can yield logical and useful results (Carpitella et al., 2024). Figure 12 illustrates an example of how Expert Choice v.11.5 software judges the inconsistency ratio 0.00.



A pair-wise comparison judgement has been made

Compare the relative importance with respect to: Physicochemical properties \ Density

	S100	C100	J100	S90C5J5	S80C10J1	S70C15J1	S60C20J2	S50C25J2	S40C30J3	S30C35J3	S20C40J4	S10C45J4	S0C50J50
S100		1.086	1.092	1.009	1.017	1.026	1.029	1.046	1.052	1.057	1.072	1.075	1.086
C100			1.005	1.077	1.068	1.059	1.056	1.038	1.033	1.027	1.013	1.011	1.0
J100				1.083	1.073	1.064	1.061	1.044	1.038	1.033	1.019	1.016	1.005
S90C5J5					1.009	1.017	1.02	1.037	1.043	1.048	1.063	1.066	1.077
S80C10J10						1.008	1.011	1.028	1.034	1.04	1.054	1.056	1.068
S70C15J15							1.003	1.02	1.025	1.031	1.045	1.048	1.059
S60C20J20								1.017	1.022	1.028	1.042	1.045	1.056
S50C25J25									1.005	1.011	1.025	1.027	1.038
S40C30J30										1.005	1.019	1.022	1.033
S30C35J35											1.014	1.016	1.027
S20C40J40												1.003	1.013
S10C45J45													1.011
S0C50J50	Incon: 0.00												

Inconsistency ratio

Figure 12: Inconsistency ratio 0.00.

To determine the consistency ratio, three calculations must be made: the principal eigenvalue, consistency index (CI), and consistency ratio (Mansor et al., 2013). The principal eigenvalue can be determined via Equation 8:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{x_i}{c_i} \tag{8}$$

where *i* is equivalent to *j* in 1, 2, 3, 4, ..., *n*, and λ_{max} is the principal eigenvalue (Cay & Uyan, 2013). Besides, Equation 9 can be deployed to obtain the principal eigenvalue:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{\sum_{j=1}^{n} a_{ij}\ x\ w_j}{w_i} \tag{9}$$

where *i* is equivalent to *j* in 1, 2, 3, 4, ..., *n*, λ_{max} is the principal eigenvalue, and *w* is the priority vector (Ali et al., 2015; Mansor et al., 2013). CI was calculated with the following Equation 10:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{10}$$

where *n* is the criteria or matrix size (Ali et al., 2015; Ali et al., 2023; Cay and Uyan, 2013; Mansor et al., 2013). The ratio of CI to random indices (RI) is known as the CR (Abudeif et al., 2015; Bagheri et al., 2021). Equation 11 can be applied as follows to calculate CR:

$$CR = \frac{CI}{RI} \tag{11}$$

For a sample size of 500, Saaty has provided the average consistencies for RI values of randomLy produced matrices up to size *11 x 11* (Abudeif et al., 2015; Ishizaka and Labib, 2009). Table 7 demonstrates the RI values for different sized matrices (Abudeif et al., 2015; Razak et al., 2022).

Table 7: The average consistency (RI values) (Abudeif et al., 2015; Razak et al., 2022).

Parameters	
Size of a matrix	**Random index**
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59

2.2.7 Step 7: Checking consistency ratio

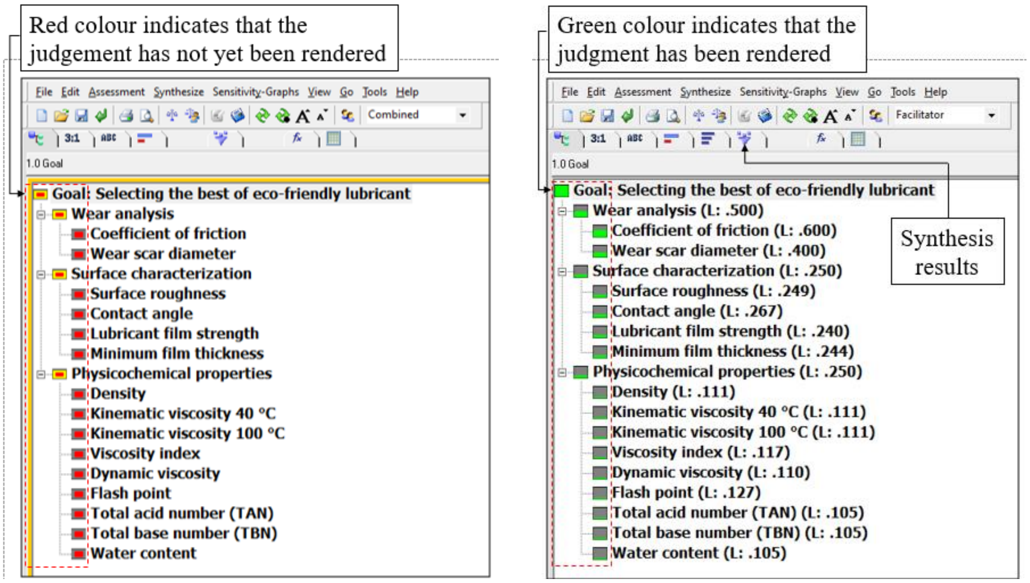
The AHP uses a CR to determine whether the decisions are generally consistent. CR ≤ 0.10 indicates that the consistency ratio is acceptable (Dweiri et al., 2016). The CR makes it possible to tally the number of mistakes during the performance of the judgment of pairwise comparison. Serious inconsistencies exist if CR is larger than 0.10. The AHP might not reach relevant findings in this condition (Cay & Uyan, 2013). Judgments should be examined and refined, and the process repeated to perform the pair-wise comparison judgement, ensuring a consistent matrix.

2.2.8 Step 8: Develop an overall priority ranking

Develop an overall priority ranking that can only be reached when the judgements are considered acceptable, which is when the CR value is less than 0.1. All first and second nodes experienced the judgement process completely if their CR value was less than 0.1.

2.2.9 Step 9: Selecting the best eco-friendly lubricant

Figure 13 shows the two conditions that existed both before and after the Expert Choice v.11.5 software was applied for judging. The red colour indicates that the judgement has not yet been fully rendered, as shown in Figure 13(a). In contrast, Figure 13(b) uses green to signify that the judgement has been completely rendered. As depicted in Figure 13(b), the synthesis results become available once all judgements are finalized, and the synthesis results indicates that the data were generated through pairwise comparisons. At this stage, the best eco-friendly lubricant can be chosen.



Red colour indicates that the judgement has not yet been rendered

Goal: Selecting the best of eco-friendly lubricant
Wear analysis
Coefficient of friction
Wear scar diameter
Surface characterization
Surface roughness
Contact angle
Lubricant film strength
Minimum film thickness
Physicochemical properties
Density
Kinematic viscosity 40 °C
Kinematic viscosity 100 °C
Viscosity index
Dynamic viscosity
Flash point
Total acid number (TAN)
Total base number (TBN)
Water content

Green colour indicates that the judgment has been rendered

Synthesis results

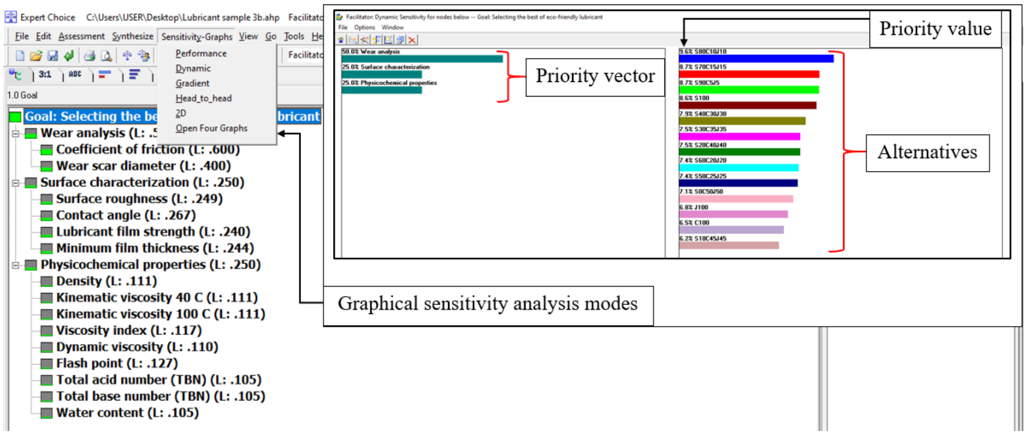
Goal: Selecting the best of eco-friendly lubricant
Wear analysis (L: .500)
Coefficient of friction (L: .600)
Wear scar diameter (L: .400)
Surface characterization (L: .250)
Surface roughness (L: .249)
Contact angle (L: .267)
Lubricant film strength (L: .240)
Minimum film thickness (L: .244)
Physicochemical properties (L: .250)
Density (L: .111)
Kinematic viscosity 40 °C (L: .111)
Kinematic viscosity 100 °C (L: .111)
Viscosity index (L: .117)
Dynamic viscosity (L: .110)
Flash point (L: .127)
Total acid number (TAN) (L: .105)
Total base number (TBN) (L: .105)
Water content (L: .105)

(a) Decision has not yet been made (b) Decision has been made

Figure 13: The judging process via Expert Choice v.11.5 software.

2.2.10 Step 10: Perform the sensitivity analysis

The executing process and modes for sensitivity analysis are displayed in Figure 14. This study uses dynamic and performance graphical sensitivity analysis modes for results verification scenarios. Three different scenarios of increasing the priority vector for the AHP main criterion were performed for the sensitivity analysis. The priority vectors for every main criterion were raised by 20%. According to the method applied by earlier researchers, the sensitivity analysis was enhanced by 20% for their investigation (Ali et al., 2015; Mansor et al., 2014; Razak et al., 2022). The earlier outcomes are fixed as comparison benchmarks. As depicted in Figure 14, by dragging either of the priority vectors in the left column, the priority value of the alternatives will alter in the right column.



Goal: Selecting the best of eco-friendly lubricant
Wear analysis (L: .500)
Coefficient of friction (L: .600)
Wear scar diameter (L: .400)
Surface characterization (L: .250)
Surface roughness (L: .249)
Contact angle (L: .267)
Lubricant film strength (L: .240)
Minimum film thickness (L: .244)
Physicochemical properties (L: .250)
Density (L: .111)
Kinematic viscosity 40 C (L: .111)
Kinematic viscosity 100 C (L: .111)
Viscosity index (L: .117)
Dynamic viscosity (L: .110)
Flash point (L: .127)
Total acid number (TBN) (L: .105)
Total base number (TBN) (L: .105)
Water content (L: .105)

50.0% Wear analysis
25.0% Surface characterization
25.0% Physicochemical properties

9.6% S80C10J10
8.7% S70C15J15
8.7% S90C5J5
8.6% S100
7.9% S40C30J30
7.5% S30C35J35
7.5% S20C40J40
7.4% S60C20J20
7.4% S50C25J25
7.1% S0C50J50
6.8% J100
6.5% C100
6.2% S10C45J45

Priority value

Priority vector

Alternatives

Graphical sensitivity analysis modes

Figure 14: The sensitivity analysis modes and implementation process.

3.0 RESULTS AND DISCUSSION

This section was divided into three main portions to determine the ultimate conclusion: the experiment and calculating results, the AHP approach using Expert Choice software results, and sensitivity results. However, the primary focus of the study is on the selection of the best eco-friendly lubricant.

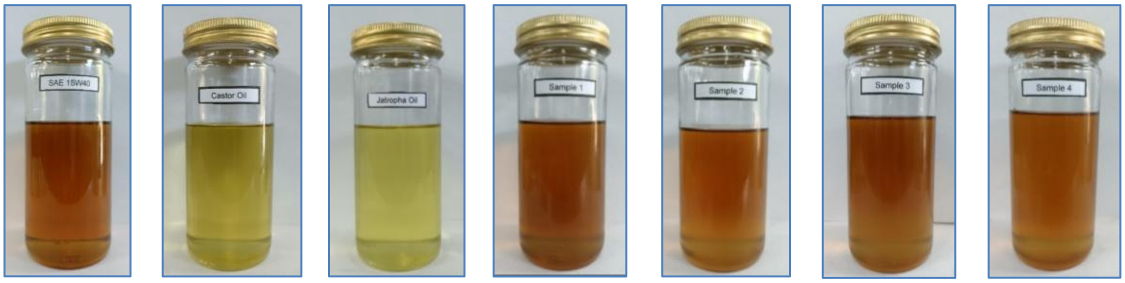
3.1 The Experimental Results

Photographs of the lubricant samples are shown in Figure 15. The results are divided into three main groups based on wear analysis, surface characterization, and physicochemical properties, as shown in Table 8, Table 9, and Table 10. The reduction of volume S100 results in bright colors of eco-friendly lubricants. Each eco-friendly lubricant shows a uniform mixture, with no precipitate formed.

3.1.1 The optimal eco-friendly lubricant selection using analytical hierarchy process

The hierarchy framework of the AHP model is composed of the objective or goal, the criteria, the sub-criteria, and the alternatives (Ali et al., 2023; Anis & Islam, 2015; Dweiri et al., 2016; Hamidah et al., 2022; Liang & Chen, 2021). Figure 16 shows the hierarchy framework model produced by Expert Choice v.11.5 software. This has been proven by the author (Grabusic and Baric, 2022), who claimed that using Expert Choice software, the hierarchy framework of the AHP model may be produced using the goal or objective, criteria, sub-criterion, and variations for the best variant choice (Grabušic & Baric, 2022). A pair-wise comparison matrix of size *n* × *n* has been created for the lower levels using one matrix in the level directly above. For each level of the hierarchy, the pair-wise comparisons provide a matrix of relative rankings. The total number of matrices is determined by the total number of elements at each level. The number of items at the lower level that each element relates to determines the order of the matrix at that level. The priority vector is first generated by building pair-wise comparison matrices (size *n* × *n*) for each of the lower levels in the hierarchy framework, one matrix for each element on the level directly above (Mansor et al., 2013). Figure 17 indicates an example of a pair-wise comparison matrix produced by Expert Choice v.11.5 software to help in understanding the aforementioned assertion.

Figure 9 provides an example of the pair-wise comparison ratios of the alternative with regard to COF computed using the Expert Choice v.11.5 software. Decisions based on Equation 6 were used to construct the collection of matrices. In accordance with Table 5, each component must be compared or judged using the Saaty scale in a pair-wise comparison. The judgements are based on Table 8, Table 9, and Table 10. A pair-wise comparison judgement example is provided in Figure 18. If S100 is significantly more important than C100, the graphical scale is 1.20. Every pair-wise comparison to C100 receives an automated reciprocal at 0.833 (1/1.20). If S100 has a weaker relative importance to S30C35J35, the graphical scale is 1.029. A reciprocal is automatically assigned for each pair-wise comparison to S30C35J35, which is 0.972 (1/1.029). This is supported by authors (Dweiri et al., 2016), who utilised this method and the Saaty scale to illustrate that AHP functions in a decision support model for supplier selection in the automotive sector (Dweiri et al., 2016).



(a) S100 (b) C100 (c) J100 (d) S90C5J5 (e) S80C10J10 (f) S70C15J15 (g) S60C20J20

(h) S50C25J25 (i) S40C30J30 (j) S30C35J35 (k) S20C40J40 (l) S10C45J45 (m) S0C50J50

Figure 15: Photograph of pure oils (a) S100, (b) C100, (c) J100, and eco-friendly lubricants (d-m).

Table 8: The main criterion (wear analysis).

Samples	**Parameters**	
	Average steady state	**Average wear scar diameter (μm)**
S100	0.0918	490
C100	0.1102	823
J100	0.1033	669
S90C5J5	0.0992	419
S80C10J10	0.0756	368
S70C15J15	0.0868	385
S60C20J20	0.1160	458
S50C25J25	0.1266	424
S40C30J30	0.1051	414
S30C35J35	0.0892	556
S20C40J40	0.1049	488
S10C45J45	0.1125	977
S0C50J50	0.0865	775

Table 9: The main criterion (surface characterization).

Samples	**Parameters**			
	Mean value of surface roughness *Ra*	**Average contact angle (°)**	**Lubricant film strength (MPa)**	**Minimum film thickness (nm)**
S100	0.7	27.5	849.02	3189.9
C100	0.9	41.3	301.11	6422.5
J100	1.3	41.2	455.36	6510.2
S90C5J5	1.0	24.8	1163.20	3142.1
S80C10J10	1.2	24.3	1503.41	3449.6
S70C15J15	1.0	29.7	1374.79	3816.3
S60C20J20	0.9	25.7	972.53	4824.7
S50C25J25	0.9	29.6	1136.03	6126.1
S40C30J30	0.8	31.3	1190.98	6467.2
S30C35J35	0.9	37.2	660.11	6128.4
S20C40J40	0.9	31.5	857.40	5899.3
S10C45J45	1.0	32.5	213.64	5725.1
S0C50J50	1.5	37.7	339.65	6286.9

Table 10: The main criterion (physicochemical properties).

Samples	Parameters								
	Density (kgm^{-3})	**Kinematic viscosity (mm^2/s)**		**Viscosity index**	**Dynamic viscosity (cP)**	**Flash point (°C)**	**Total acid number (mgKOH/g)**	**Total base number (mgKOH/g)**	**Water content (ppm)**
		40 °C	**100 °C**						
S100	870.0	87.87	14.29	169	76.45	198	7.83	4.57	2604.7
C100	945.0	237.40	18.99	88	224.35	200	6.83	6.41	2485.6
J100	950.0	241.14	18.83	97	229.08	188	2.73	0.36	1951.8
S90C5J5	877.5	85.12	12.38	141	74.69	200	6.18	7.76	2388.2
S80C10J10	885.0	97.43	12.57	124	86.23	202	5.45	4.50	2063.8
S70C15J15	892.5	112.86	10.72	74	100.72	190	4.08	1.91	2198.5
S60C20J20	895.0	161.42	10.56	39	144.48	190	6.96	2.14	1970.8
S50C25J25	910.0	229.25	12.01	30	208.62	188	5.50	2.18	1820.4
S40C30J30	915.0	247.82	13.20	36	226.75	177	6.64	3.07	1788.6
S30C35J35	920.0	226.89	14.43	53	208.74	167	4.35	3.66	1855.6
S20C40J40	932.5	211.11	15.62	70	196.86	164	3.56	1.74	1793.6
S10C45J45	935.0	201.05	16.35	82	187.98	157	3.44	0.27	1434.8
S0C50J50	945.0	229.74	18.70	89	217.11	144	2.63	3.34	1356.9

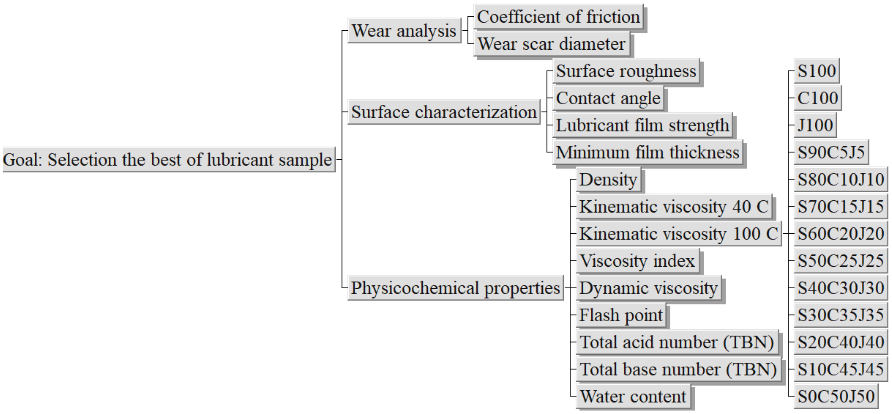
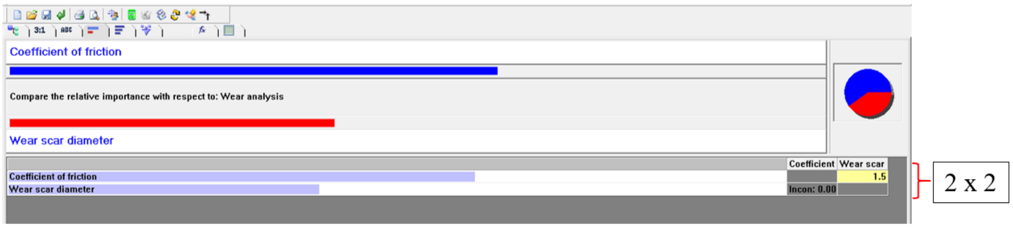


Figure 16: Hierarchy framework model view.

Figure 11 displays the results of the whole judgement on priority vectors, with criterion weights for each of the main criteria and sub-criteria. The evaluation of criterion weight is permitted based on knowledge and judgement. It is more crucial to place an emphasis on selection criteria, including knowledge, experience, and background (Shafaghat et al., 2019). Based on Figure 11, Figure 19, Figure 20 and Figure 21 were generated to display a deeper examination of the results of weightage value and ranking for each main criterion, sub-criteria, and alternative. The weightage values for each main criterion at the second level of the hierarchy framework are displayed in Figure 19. Figure 19 demonstrates that wear analysis, which has the highest ranking and a score of 0.500, is followed by surface characterization and physicochemical properties, each of which has a score of 0.250. It also reveals that the second-level hierarchy has an overall inconsistency of 0.00. There is more attention on wear analysis with a higher criterion weight than the other main criteria since eco-friendly lubricants are being developed as a lubricant for vehicle engines. According to previous research, lubricants significantly contribute to the expansion of the worldwide industrial and commercial sectors by reducing wear and friction in mechanical contacts (Maleque et al., 2003; Quinchia et al., 2014).

Figure 20 shows the weighted values for each sub-criterion at the third level of the hierarchy framework. According to Figure 20(a), the criteria weight of COF has the highest score of 0.60 as compared to WSD under the wear analysis group. The COF is given more weight because reducing friction is the primary purpose of eco-friendly lubricants. Lubrication is a particularly effective approach for minimising friction and wear between rubbing surfaces (Dweiri et al., 2016). The criteria weights for each contact angle, surface roughness, minimum film thickness, and lubricant film strength under the surface characterization group are 0.267, 0.249, 0.244, and 0.240, respectively, as shown in Figure 20(b). The weight of the contact angle is greater than that of the other. Contact angle is given priority since measuring it is one of the best ways to determine how well a lubricant will adhere to the surface to which it has been applied. Lubricants have the capacity to spread or deposit across the surface on which they are applied or to form a thin film of boundary over the surface of contact (Narayanasarma and Kuzhiveli, 2021). The ranking and criterion weight for physicochemical properties can be seen in Figure 20(c), while the flash point denotes the sub-criteria with the highest score (0.127) in comparison to the others. Flash point is given more weight because it is one of the most important considerations in determining the quality of a lubricant and whether it is appropriate for a given application. In order to avoid fires while performing tasks such as lubricating engines, lubricants must have flash points that are much higher (Samuel Gemsprim et al., 2020) than the peak application temperature (Folayan et al., 2019). A 0.00 overall inconsistency exists at the third level of the hierarchy framework.



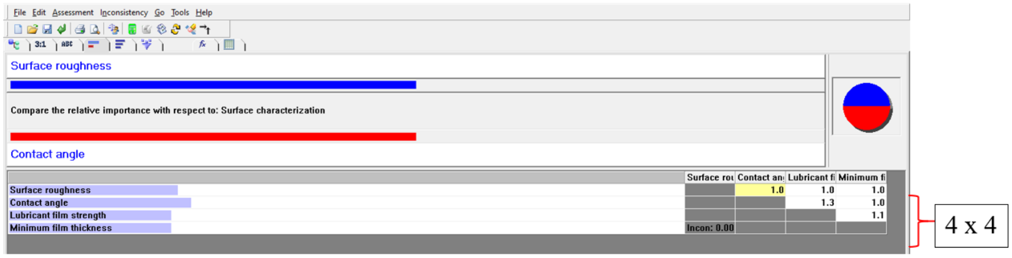
Coefficient of friction

Compare the relative importance with respect to: Wear analysis

Wear scar diameter

	Coefficient	Wear scar
Coefficient of friction		1.5
Wear scar diameter	Incon: 0.00	

(a) Pair-wise comparison matrix for wear analysis (first node).



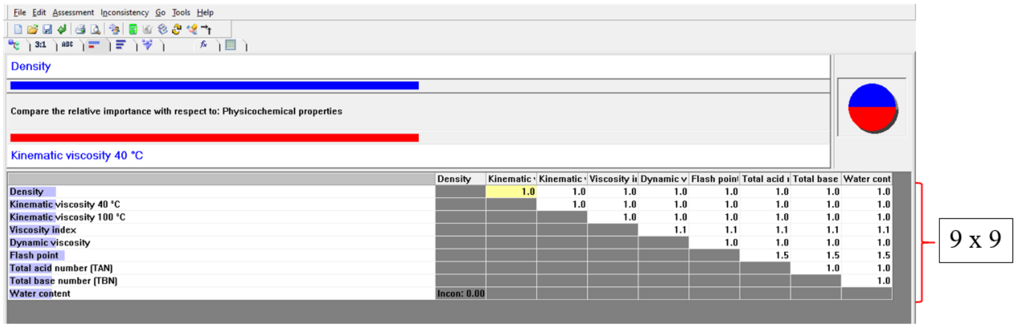
Surface roughness

Compare the relative importance with respect to: Surface characterization

Contact angle

	Surface rou	Contact an	Lubricant fi	Minimum fi
Surface roughness		1.0	1.0	1.0
Contact angle			1.3	1.0
Lubricant film strength				1.1
Minimum film thickness	Incon: 0.00			

(b) Pair-wise comparison matrix for surface characterization (first node).



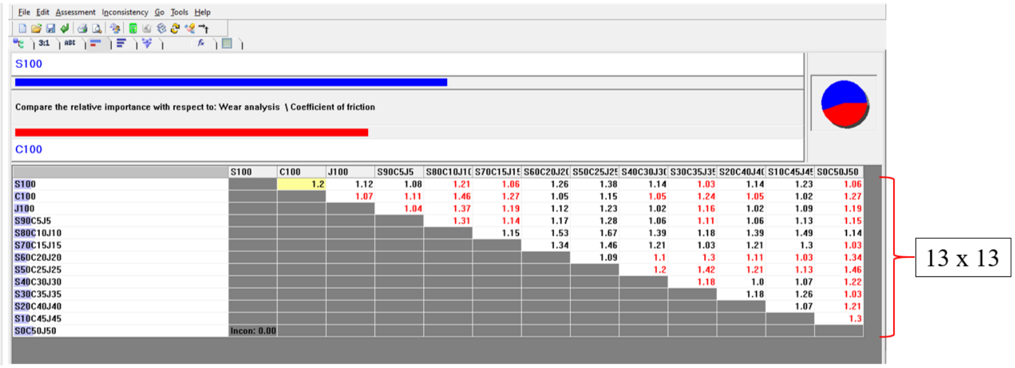
Density

Compare the relative importance with respect to: Physicochemical properties

Kinematic viscosity 40 °C

	Density	Kinematic	Kinematic	Viscosity i	Dynamic v	Flash point	Total acid	Total base	Water cont
Density		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Kinematic viscosity 40 °C			1.0	1.0	1.0	1.0	1.0	1.0	1.0
Kinematic viscosity 100 °C				1.0	1.0	1.0	1.0	1.0	1.0
Viscosity index					1.1	1.1	1.1	1.1	1.1
Dynamic viscosity						1.0	1.0	1.0	1.0
Flash point							1.5	1.5	1.5
Total acid number (TAN)								1.0	1.0
Total base number (TBN)									1.0
Water content	Incon: 0.00								

(c) Pair-wise comparison matrix for physicochemical properties (first node).



S100

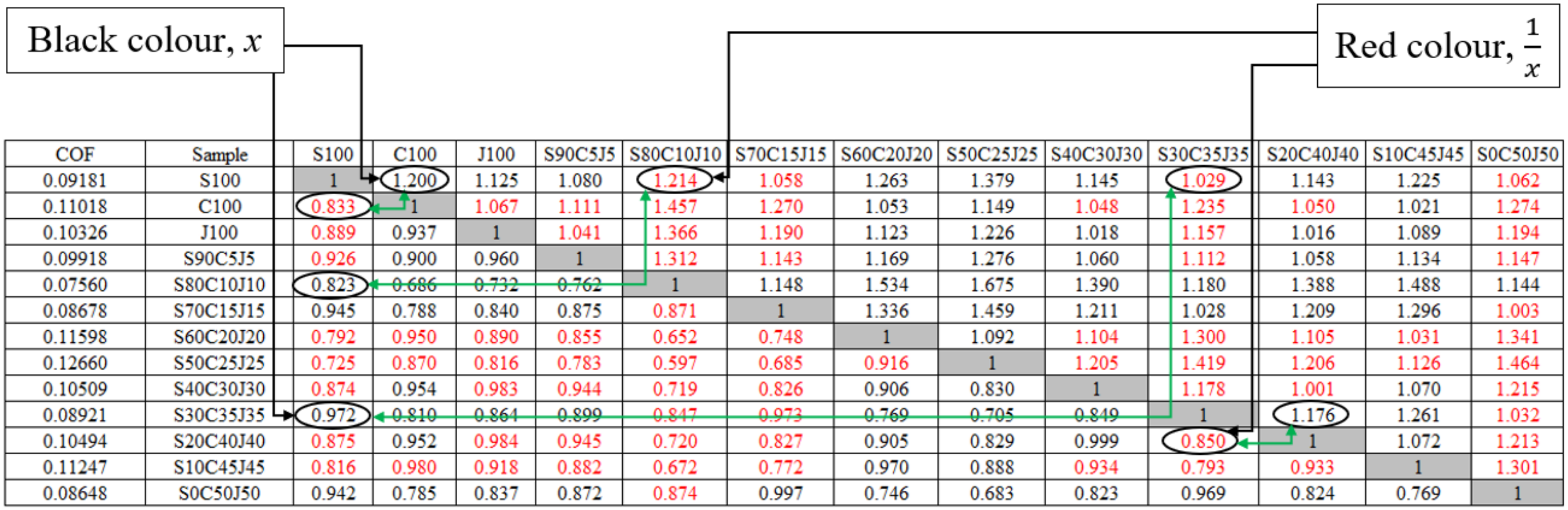
Compare the relative importance with respect to: Wear analysis \ Coefficient of friction

C100

	S100	C100	J100	S90C5J5	S80C10J1(	S70C15J1!	S60C20J2(	S50C25J2!	S40C30J3(	S30C35J3!	S20C40J4(	S10C45J4!	S0C50J50
S100		1.2	1.12	1.08	1.21	1.06	1.26	1.38	1.14	1.03	1.14	1.23	1.06
C100			1.07	1.11	1.46	1.27	1.05	1.15	1.05	1.24	1.05	1.02	1.27
J100				1.04	1.37	1.19	1.12	1.23	1.02	1.16	1.02	1.09	1.19
S90C5J5					1.31	1.14	1.17	1.28	1.06	1.11	1.06	1.13	1.15
S80C10J10						1.15	1.53	1.67	1.39	1.18	1.39	1.49	1.14
S70C15J15							1.34	1.46	1.21	1.03	1.21	1.3	1.03
S60C20J20								1.09	1.1	1.3	1.11	1.03	1.34
S50C25J25									1.2	1.42	1.21	1.13	1.46
S40C30J30										1.18	1.0	1.07	1.22
S30C35J35											1.18	1.26	1.03
S20C40J40												1.07	1.21
S10C45J45													1.3
S0C50J50	Incon: 0.00												

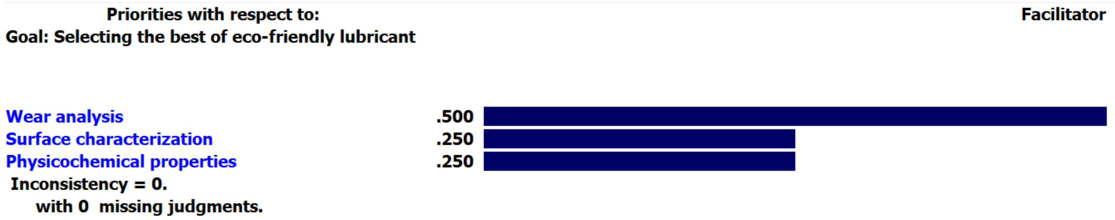
(d) Pair-wise comparison matrix for coefficient of friction (second node).

Figure 17: An example of a pair-wise comparison matrix.



COF	Sample	S100	C100	J100	S90C5J5	S80C10J10	S70C15J15	S60C20J20	S50C25J25	S40C30J30	S30C35J35	S20C40J40	S10C45J45	S0C50J50
0.09181	S100	1	1.200	1.125	1.080	1.214	1.058	1.263	1.379	1.145	1.029	1.143	1.225	1.062
0.11018	C100	0.833	1	1.067	1.111	1.457	1.270	1.053	1.149	1.048	1.235	1.050	1.021	1.274
0.10326	J100	0.889	0.937	1	1.041	1.366	1.190	1.123	1.226	1.018	1.157	1.016	1.089	1.194
0.09918	S90C5J5	0.926	0.900	0.960	1	1.312	1.143	1.169	1.276	1.060	1.112	1.058	1.134	1.147
0.07560	S80C10J10	0.823	0.686	0.732	0.762	1	1.148	1.534	1.675	1.390	1.180	1.388	1.488	1.144
0.08678	S70C15J15	0.945	0.788	0.840	0.875	0.871	1	1.336	1.459	1.211	1.028	1.209	1.296	1.003
0.11598	S60C20J20	0.792	0.950	0.890	0.855	0.652	0.748	1	1.092	1.104	1.300	1.105	1.031	1.341
0.12660	S50C25J25	0.725	0.870	0.816	0.783	0.597	0.685	0.916	1	1.205	1.419	1.206	1.126	1.464
0.10509	S40C30J30	0.874	0.954	0.983	0.944	0.719	0.826	0.906	0.830	1	1.178	1.001	1.070	1.215
0.08921	S30C35J35	0.972	0.810	0.864	0.899	0.847	0.973	0.769	0.705	0.849	1	1.176	1.261	1.032
0.10494	S20C40J40	0.875	0.952	0.984	0.945	0.720	0.827	0.905	0.829	0.999	0.850	1	1.072	1.213
0.11247	S10C45J45	0.816	0.980	0.918	0.882	0.672	0.772	0.970	0.888	0.934	0.793	0.933	1	1.301
0.08648	S0C50J50	0.942	0.785	0.837	0.872	0.874	0.997	0.746	0.683	0.823	0.969	0.824	0.769	1

Figure 18: Coefficient of friction pair-wise comparisons with a 0.00 inconsistency ratio.


Priorities with respect to:
Goal: Selecting the best of eco-friendly lubricant
Facilitator

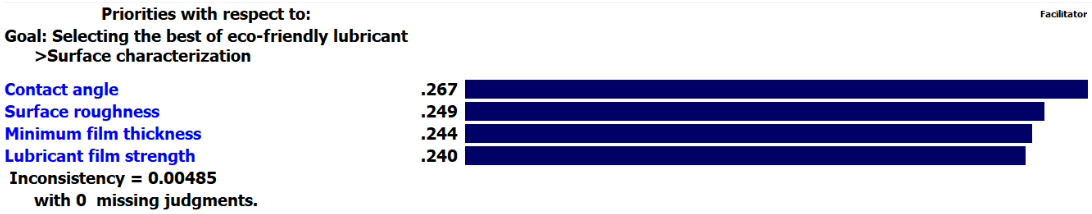
Wear analysis .500
Surface characterization .250
Physicochemical properties .250
Inconsistency = 0.
with 0 missing judgments.

Figure 19: Ranking and weightage criteria at the second level of the hierarchy framework.


Priorities with respect to:
Goal: Selecting the best of eco-friendly lubricant
>Wear analysis
Facilitator

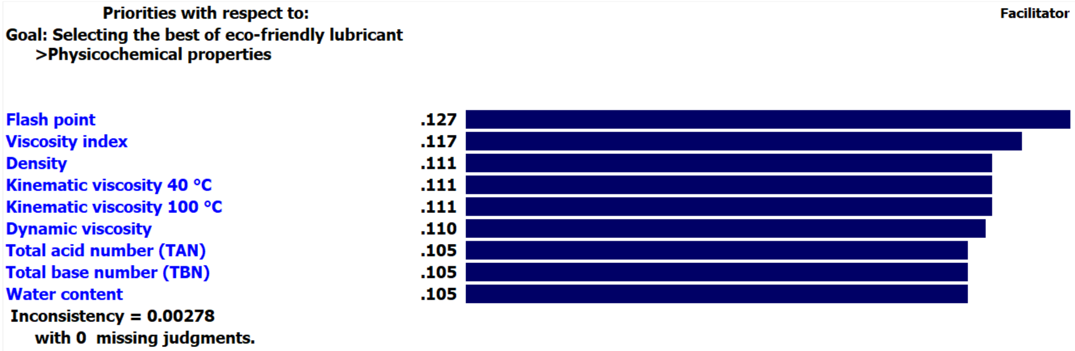
Coefficient of friction .600
Wear scar diameter .400
Inconsistency = 0.
with 0 missing judgments.

(a) Wear analysis.


Priorities with respect to:
Goal: Selecting the best of eco-friendly lubricant
>Surface characterization
Facilitator

Contact angle .267
Surface roughness .249
Minimum film thickness .244
Lubricant film strength .240
Inconsistency = 0.00485
with 0 missing judgments.

(b) Surface characterization.


Priorities with respect to:
Goal: Selecting the best of eco-friendly lubricant
>Physicochemical properties
Facilitator

Flash point .127
Viscosity index .117
Density .111
Kinematic viscosity 40 °C .111
Kinematic viscosity 100 °C .111
Dynamic viscosity .110
Total acid number (TAN) .105
Total base number (TBN) .105
Water content .105
Inconsistency = 0.00278
with 0 missing judgments.

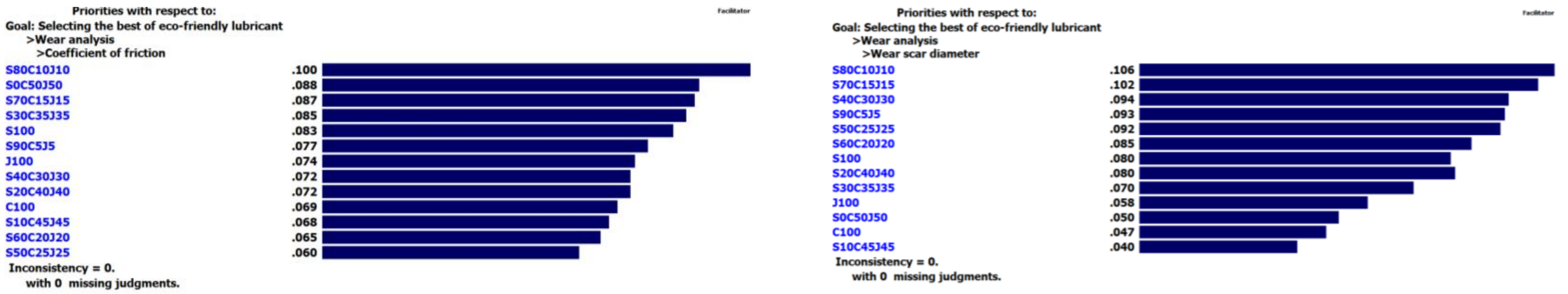
(c) Physicochemical properties.

Figure 20: Ranking and weightage criteria at the third level of the hierarchy framework are (a) wear analysis, (b) surface characterization, and (c) physicochemical properties.

The ranking and weighting values for each alternative at the fourth level of the hierarchy framework are presented in Figure 21(a-o). Each judgement produced a unique set of outcomes, as shown in Figure 21(a-o). In addition, the pair-wise comparisons at the fourth level of the hierarchy framework have an overall consistency ratio of 0.00. The Expert Choice v.11.5 software compiles the pair-wise comparison with regard to the goal (first level) after all judgements have been recorded. The best eco-friendly lubricant was determined utilising a synthesis of the goal and the overall inconsistency ratio computed from the fourth level to the second level. Finally, S80C10J10 was chosen as the best eco-friendly lubricant by the AHP method, applying Expert Choice v.11.5 software, as illustrated in Figure 22. The highest priority value for S80C10J10 was 0.096, or 9.6%. Additionally, the overall CR for the analysis was discovered to be 0.00, which is within the CR recommended limit of 0.10 or 10%, demonstrating that the subjective judgement used throughout the study is very consistent and the conclusions given by the analysis are acceptable. Ali et al., 2023 stated that a pair comparison matrix < 1 is the desired result. Furthermore, the authors (Ali et al., 2015) observed that the judgement was highly consistent because the total inconsistency following synthesis in terms of the goal was 0.01. The level fell within the range that was acceptable. Therefore, the decision was completely trustworthy (Ali et al., 2015).

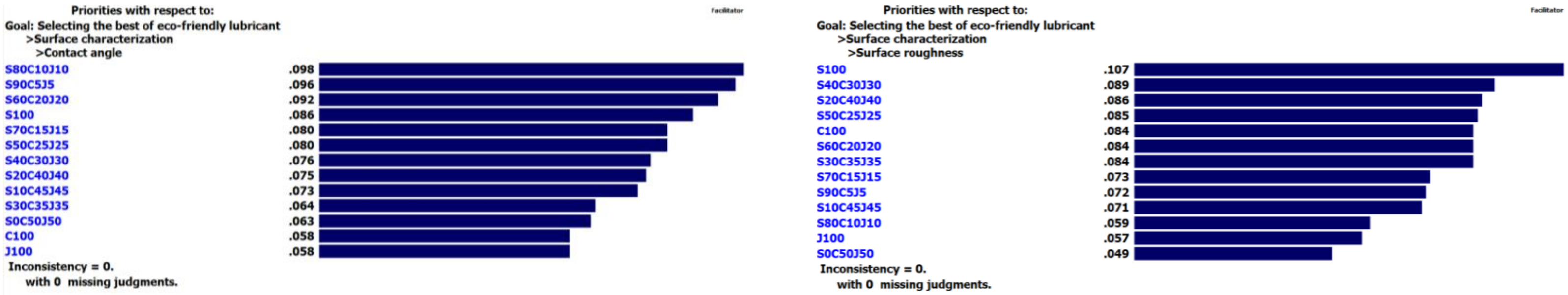
3.1.2 Results Verification of Analytical Hierarchy Process using Sensitivity Analysis

Sensitivity analysis is applied to determine the optimal decision alternative by examining the various factors that affect the choice. Sensitivity analysis is applied to validate the findings and fine-tune the judgement (Ali et al., 2015). Sensitivity analysis scenarios must be conducted in order to acquire greater confidence in the material selections and to further conclude the judgement of what is most appropriate. In this study, three scenarios of modifying the priority vector for the AHP primary criterion were run using the Expert Choice v.11.5 software. Figure 23(a) and Figure 24(a) illustrate dynamic sensitivity and performance sensitivity for the initial results of using Expert Choice v.11.5 software to select the best eco-friendly lubricant, respectively. Both graphs are split into two sections, with part one representing the priority vector and part two representing the alternative, as seen in Figure 14. Figure 23(a) explains that the dynamic sensitivity for an initial result of the priority vector for wear analysis is 50.0%, surface characterization is 25.0%, and physicochemical properties are 25.0%. Priority vectors for each main criterion have been increased by 20%. The previous study used Expert Choice v.11.5 software and adjusted each primary criterion by a 20% increase for the four scenarios in the sensitivity analysis (Razak et al., 2022). In addition, using Expert Choice v.11.5 software, the researchers increased the values of the priority vector of the key criteria, namely physical, mechanical, and cost, by 20% (Ali et al., 2015).



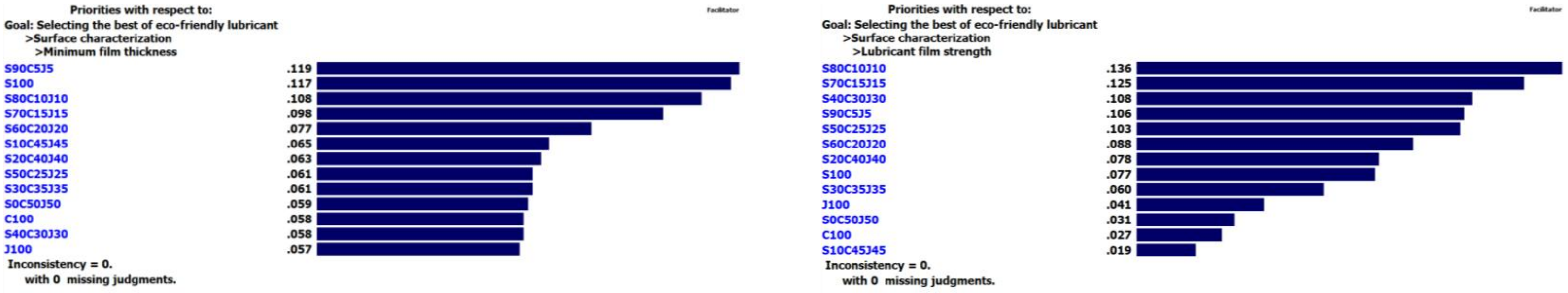
(a) Alternatives with regard to coefficient of friction.

(b) Alternatives with regard to wear scar diameter.



(c) Alternatives with regard to contact angle.

(d) Alternatives with regard to surface roughness *Ra*.

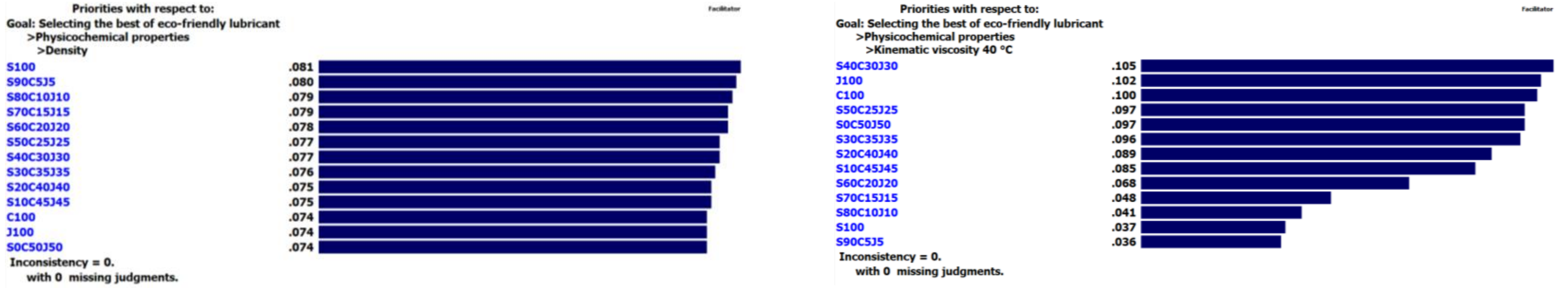


(e) Alternatives with regard to minimum film thickness.

(f) Alternatives with regard to lubricant film strength.

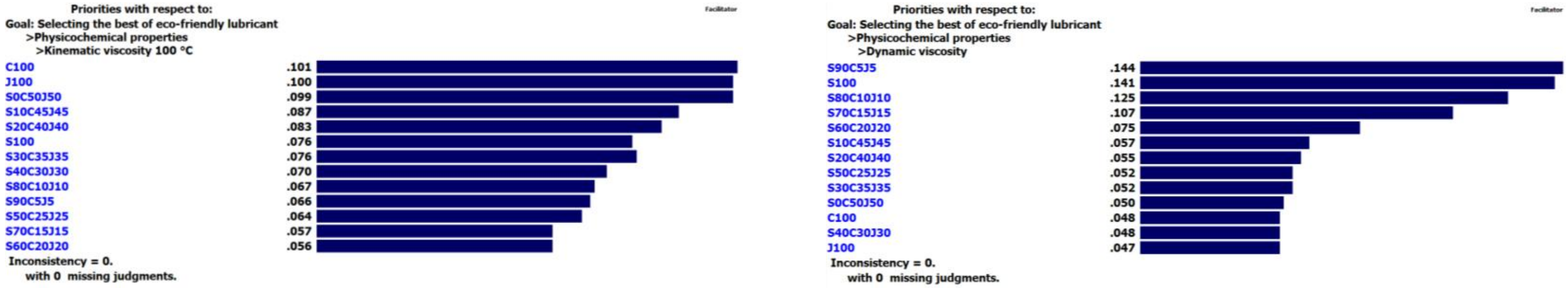
(g) Alternatives with regard to flash point.

(h) Alternatives with regard to viscosity index.



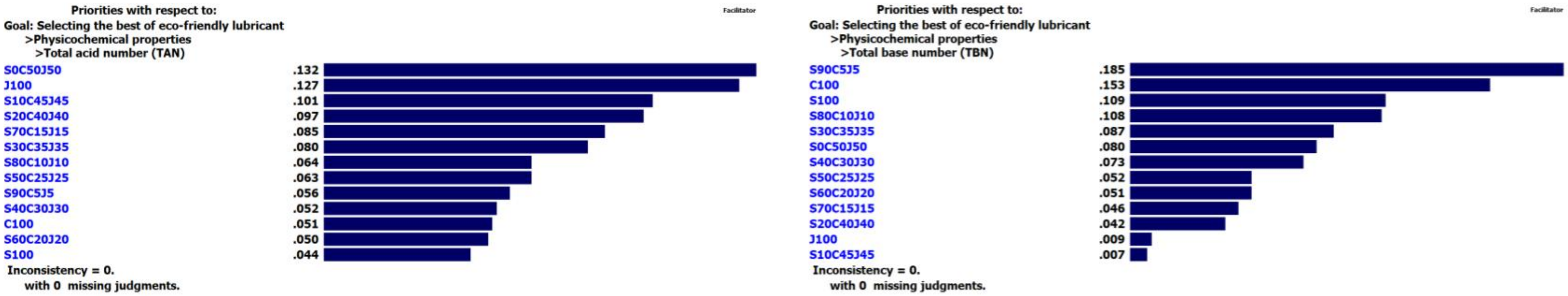
(i) Alternatives with regard to density.

(j) Alternatives with regard to kinematic viscosity 40 °C.



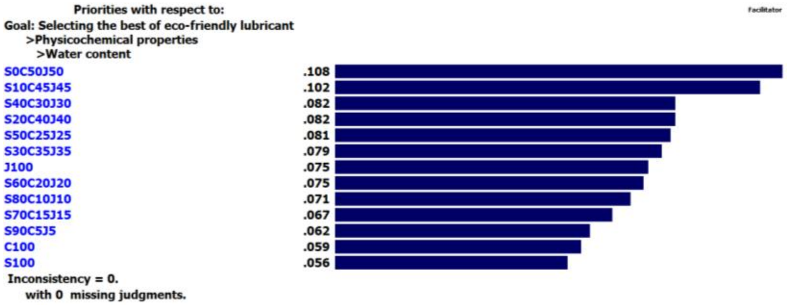
(k) Alternatives with regard to kinematic viscosity 100 °C.

(l) Alternatives with regard to dynamic viscosity.



(m) Alternatives with regard to total acid number.

(n) Alternatives with regard to total base number.



(o) Alternatives with regard to water content.

Figure 21: Ranking and weightage criteria at the fourth level of the hierarchy: (a-o) alternatives with regard to sub-criteria.

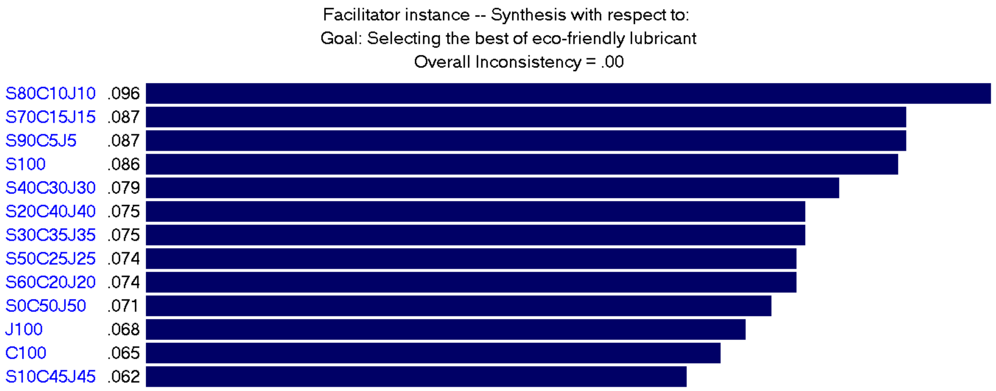
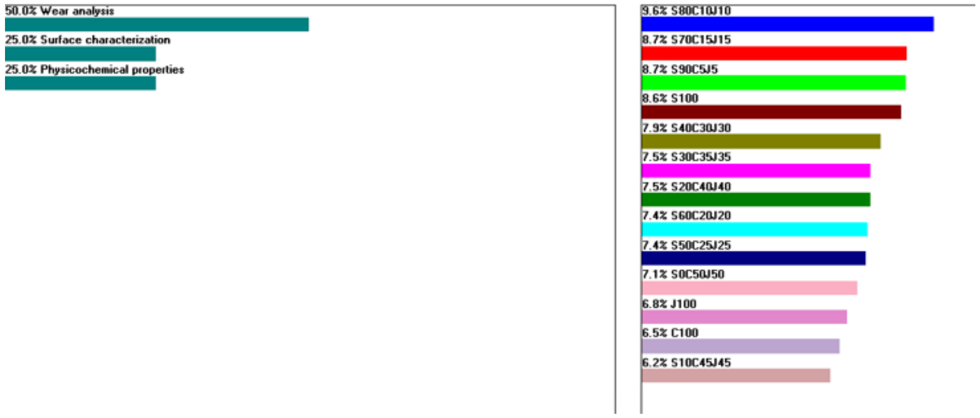
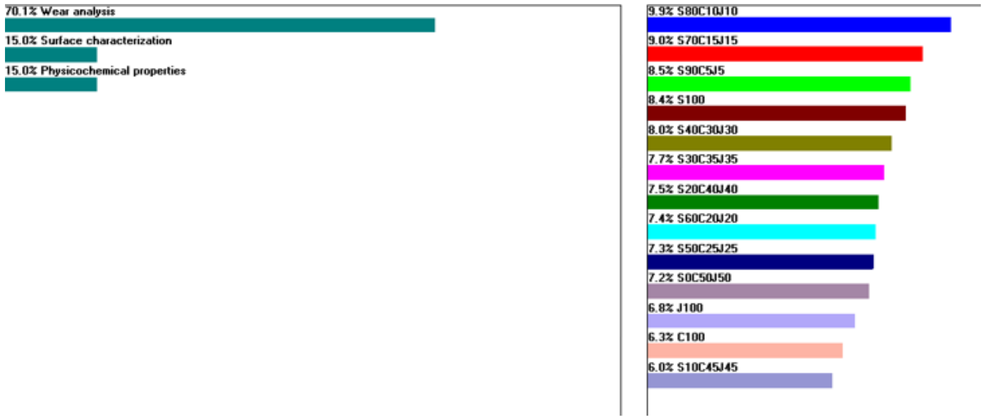


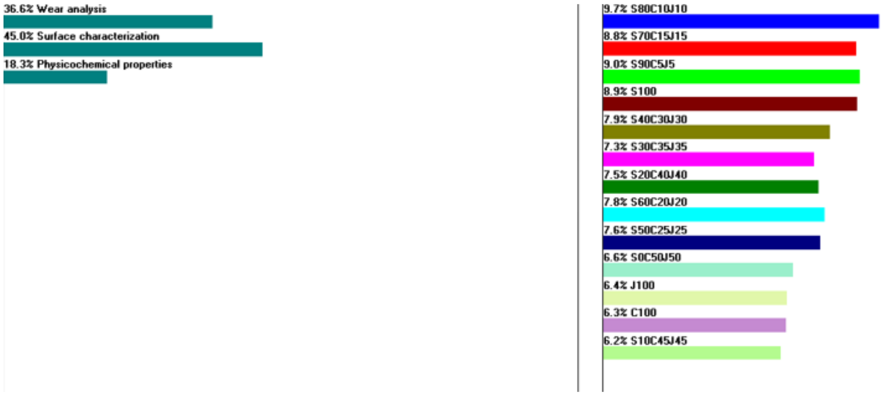
Figure 22: Overall results in selecting the best eco-friendly lubricant.



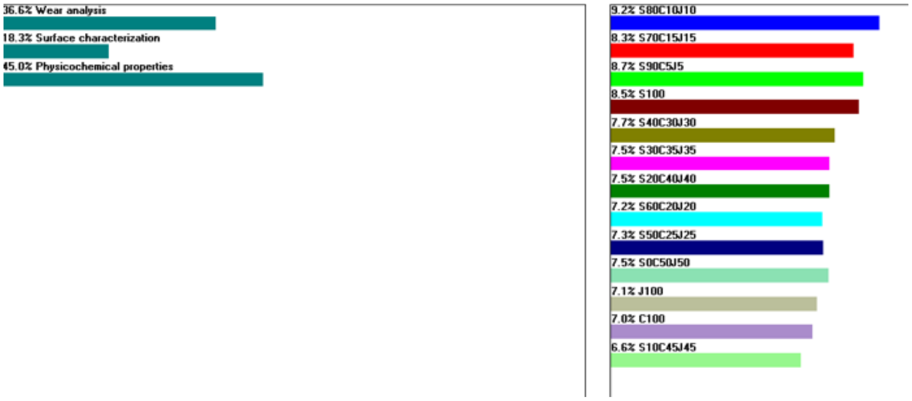
(a) Dynamic sensitivity graph for an initial result.



(b) Wear analysis has increased from 50.0% to 70.0%.

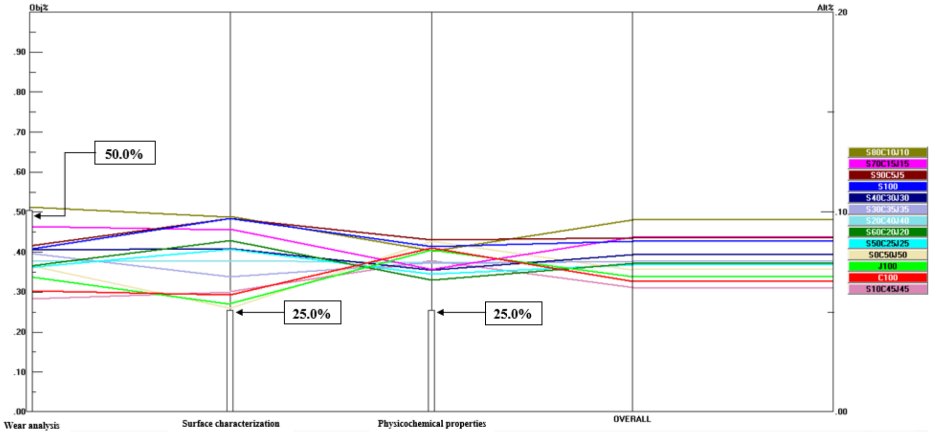


(c) Surface characterization has increased from 25.0% to 45.0%.

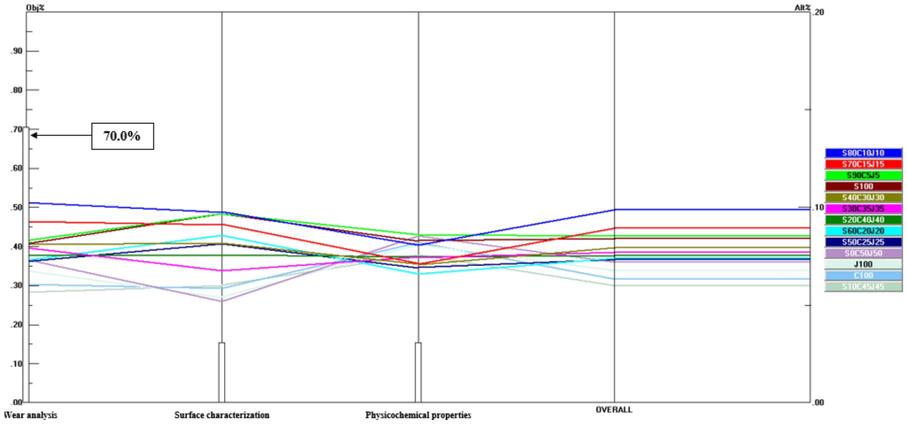


(d) Physicochemical properties have increased from 25.0% to 45.0%.

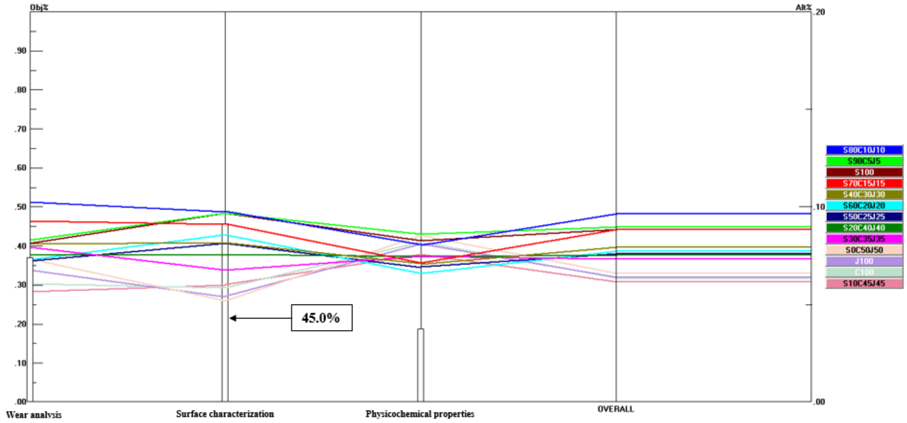
Figure 23: (a) Dynamic sensitivity graph for the initial results of the priority vector, and the priority vector increased by 20% for (b) wear analysis, (c) surface characterization, and (d) physicochemical properties.



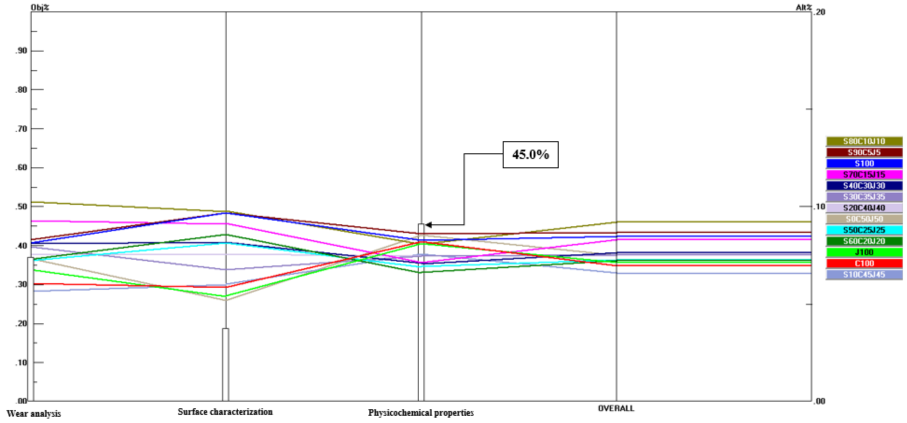
(a) Performance sensitivity graph for an initial result.



(b) Wear analysis has increased from 50.0% to 70.0%.



(c) Surface characterization has increased from 25.0% to 45.0%.



(d) Physicochemical properties have increased from 25.0% to 45.0%.

Figure 24: (a) Performance sensitivity graph for the initial results of the priority vector, and the priority vector increased by 20% for (b) wear analysis, (c) surface characterization, and (d) physicochemical properties.

Table 11: The overall ranking of alternatives for the original results in comparison to the wear analysis.

Rank	Parameters			
	Wear analysis			
	Initial results		**Increased by 20%**	
	Samples	**Priority vector (50%)**	**Samples**	**Priority vector (70%)**
1	S80C10J10	9.6	S80C10J10	9.9
2	S70C15J15	8.7	S70C15J15	9.0
3	S90C5J5	8.7	S90C5J5	8.5
4	S100	8.6	S100	8.4
5	S40C30J30	7.9	S40C35J35	8.0
6	S30C35J35	7.5	S30C35J35	7.7
7	S20C40J40	7.5	S20C40J40	7.5
8	S60C20J20	7.4	S60C20J20	7.4
9	S50C25J25	7.4	S50C25J25	7.3
10	S0C50J50	7.1	S0C50J50	7.2
11	J100	6.8	J100	6.8
12	C100	6.5	C100	6.3
13	S10C45J45	6.2	S10C45J45	6.0

Table 12: The overall ranking of alternatives for the original results in comparison to the surface characterization.

Rank	Parameters			
	Surface characterization			
	Initial results		**Increased by 20%**	
	Samples	**Priority vector (25%)**	**Samples**	**Priority vector (45%)**
1	S80C10J10	9.6	S80C10J10	9.7
2	S70C15J15	8.7	S90C5J5	9.0
3	S90C5J5	8.7	S100	8.9
4	S100	8.6	S70C15J15	8.8
5	S40C30J30	7.9	S40C30J30	7.9
6	S30C35J35	7.5	S60C20J20	7.8
7	S20C40J40	7.5	S50C25J25	7.6
8	S60C20J20	7.4	S20C40J40	7.5
9	S50C25J25	7.4	S30C35J35	7.3
10	S0C50J50	7.1	S0C50J50	6.6
11	J100	6.8	J100	6.4
12	C100	6.5	C100	6.3
13	S10C45J45	6.2	S10C45J45	6.2

Table 13: The overall ranking of alternatives for the original results in comparison to physicochemical properties.

Rank	**Parameters**			
	Physicochemical properties			
	Initial results		**Increased by 20%**	
	Samples	**Priority vector (25%)**	**Samples**	**Priority vector (45%)**
1	S80C10J10	9.6	S80C10J10	9.2
2	S70C15J15	8.7	S90C5J5	8.7
3	S90C5J5	8.7	S100	8.5
4	S100	8.6	S70C15J15	8.3
5	S40C30J30	7.9	S40C30J30	7.7
6	S30C35J35	7.5	S30C35J35	7.5
7	S20C40J40	7.5	S20C40J40	7.5
8	S60C20J20	7.4	S0C50J50	7.5
9	S50C25J25	7.4	S50C25J25	7.3
10	S0C50J50	7.1	S60C20J20	7.2
11	J100	6.8	J100	7.1
12	C100	6.5	C100	7.0
13	S10C45J45	6.2	S10C45J45	6.6

According to Figure 23(a), changing the priority vector, which is comprised of wear analysis, surface characterization, and physicochemical properties, would therefore vary the final ranking of the alternative, as illustrated in Figure 23(b), Figure 23(c), and Figure 23(d), respectively. Since the priority sensitivity of every criterion or alternative has been altered, it would be possible to see the extent of alterations that would be necessary for other criteria or alternatives as a result of sensitivity analysis (Bagheri et al., 2021). S80C10J10 is the first ranking in the initial result for performance sensitivity analysis, as shown in Figure 24(a). The increment of each priority vector increased by 20%, resulting in the wear analysis increasing to 70.0%, surface characterization increasing to 45.0%, and physiochemical properties increasing by 45.0%. This change in the ranking of alternatives is shown in the performance sensitivity graphs for the main criteria with regard to the goal when the priority vector has increased by 20% in Figure 24(b), Figure 24(c), and Figure 24(d), and S80C10J10 reaches the top ranking in these three graphs. As seen in Figure 23(b), Figure 23(c), and Figure 23(d), the top ranking is S80C10J10 with values of 9.9%, 9.7%, and 9.2%, respectively. The overall ranking of alternatives for the original results, compared to the wear analysis, surface characterization, and physicochemical results after a 20% increase, is shown in Table 11, Table 12, and Table 13, respectively. It should be noted that the results show that S80C10J10 is the most suitable material for three of the scenarios and is consistent with the decision ranking obtained earlier (Figure 23(a) and Figure 24(a)). Each priority vector, such as wear analysis, surface characterization, and physicochemical properties, is increased by 20%, respectively. S80C10J10 is the undisputed winner in all three simulated scenarios. Thus, S80C10J10 validates earlier findings that the formulation of 80% S100, 10% C100, and 10% J100 is the most suitable option as an eco-friendly lubricant for lubrication. This finding is supported by the authors (Mansor et al., 2013), who changed the overall rank of the alternatives and increased each main criterion priority vector by 20% (Mansor et al., 2013). Their findings demonstrate that kenaf bast fiber is the most suitable material because it dominates two out of three simulated scenarios and validates earlier results (Mansor et al., 2014).

4.0 CONCLUSION

S80C10J10 was selected as the best eco-friendly lubricant by the AHP technique utilizing Expert Choice v.11.5 software, with the highest priority value of 0.096, or 9.6%. The total CR for the analysis was found to be 0.00, which is within the acceptable CR limit of 0.10 or 10%. A sensitivity analysis was carried out to verify the result. According to the performance sensitivity graphs, S80C10J10 is ranked first with values of 9.9%, 9.7%, and 9.2%, respectively. As a result, in all three simulated scenarios, S80C10J10 emerged as the best candidate material, further verifying and boosting trust in the results of the AHP method. The formulation S80C10J10 (80% S100, 10% C100 and 10% J100) proved to be the best eco-friendly lubricant. Even though selecting the best eco-friendly lubricant was challenging and difficult, MCDM via the AHP method proved to be very effective in solving problems for selecting the candidate.

ACKNOWLEDGEMENT

The author, Juliana Basiron, would like to thank the Ministry of Education Malaysia for her PhD sponsorship. The authors gratefully acknowledge contributions from the members of the Green Tribology and Engine Performance (G-TriboE) Research Group, Centre for Advanced Research on Energy (CARe), Universiti Teknikal Malaysia Melaka (UTeM).

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