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FEASIBILITY AND COSTS OF PREDICTIVE MAINTENANCE VIA OIL ANALYSIS IN AGRICULTURAL EQUIPMENT

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Abstract. *Agricultural activities depend largely on mechanical equipment and so availability of machines is a key component to guarantee on-schedule operations. In association with a local service provider of this segment, feasibility of predictive maintenance through oil analysis was assessed. Wear particles and contaminants were measured via spectrometry analysis which is one of most important tools for lubricant assessment. Water content and viscosity were also evaluated. Samples were analyzed by a tribology laboratory and results for viscosity, Fe content and contaminant levels were compared to acceptable limits. Results provided information about condition of engine, final reduction gearbox and differential gearbox, which are critical component for tractors. Problems like excessive wear particles and water content revealed root causes like dust contamination, defective seals and leakage in oil intercooler. Costs of repair and inspection due to predictive maintenance were compared to costs that would result from corrective maintenance. Oil analysis permitted considerable maintenance economy compared to parts and services necessary when tractor breaks down. Since unavailability of equipment may also cause loss of profit, product and clients, this predictive method can be considered effective and advantageous for agriculturists. Additionally it also benefits local service provider by selling assistance plans and increasing customer loyalty.*

Keywords: *predictive maintenance, lubricant analysis, contaminant level, agricultural equipment*

1. INTRODUCTION

Agricultural activities benefit largely from automation and use of mechanical equipment, and crop demand would not be met without utilization of this techniques. Profitability and productivity in monoculture farms are greatly enhanced through use of mechanized planters, plows, harvester and machines for application of fertilizers and agrochemicals (Fralely, 2017). Consequently, availability of equipment is a key component for farmers, since agricultural operations occur in a tight schedule.

Maintenance of such machines has usually been of corrective or preventive type as affirmed by Da Costa et. al. (2015). According to (Pinto and Nascif, 2001) the first consists of restoring the system to its original performance when a part breaks or malfunctions, while the second one is based on periodic change of specific components according to criteria established by manufacturer recommendations and user experience. This approaches are not considered the most efficient by Camargo et. al. (2014), mostly because in corrective method it is not possible to plan production stop and labor hours, while in preventive strategy the part is replaced wheatear or not it reached its end life. Once the inspection intervals of the later are defined by the Original Equipment Manufacturer (OEM) and historical observations by user, these periods are usually conservative and obsolete, and also rigid concerning technical needs. The associated substitution of well-functioning parts leads to increase in costs.

Predictive approach on the other side is based on constant monitoring of parameters and signals that indicate machine condition and component remaining life. As shown by Raposo et. al. (2019), the possible techniques include vibration analysis, thermography, visual inspection, electrical signatures, ultrasonic measurements, performance parameters and inspection of in-service lubricants. Furthermore, the use of computer tools enables analysis, recording and control of the obtained data, allowing the establishment of fault trend curves.

According to Otani and Machado (2008), this method requires more experienced and costly labor and techniques but results in better availability since machine can be inspected and serviced in convenient times while maximum performance can be achieved during work hours. For this reason, this method is being widely applied nowadays in after sale services, not only as income source but also to increase customer satisfaction and brand value. Carnero (2006) lists other advantages: enhanced safety and hence lower insurance costs; easier checking of quality requirements which facilitates attendance of ISO 9000 standard; lesser need of overproduction capacity and spare parts; better scheduling of maintenance actions and staff allocation; support for design phase of equipment; historical information for each piece of equipment allows optimization of maintenance plan by focusing on components which are more critical or more prone to fail.

Behera and Sahoo (2015) claim that predictive method has proven to be effective in reducing maintenance costs, which composes a high portion of a plant's budget, being extremely necessary for equipment whose stoppage stalls production line. Zheng et. al. (2018) showed that its application permits to extend life of parts and stretch preventive intervals practiced, achieving a reduction of 13.7% in inspection frequency. Valis et. al. (2016) states that this strategy which can also be called Condition Based Maintenance (CBM) is very useful for specific industrial systems and machines where there are no well-defined thresholds or prescriptions for fixed-time maintenance intervals from international standards.

Many works have been carried in this area with the objective of modelling machine wear as an attempt to predict equipment state based on wear particle analysis, particle counting and particle size distribution. Raadnui (2015) studied wear debris generated in the interface of seals and rotating parts and found that geometry of particles is related with wear phenomenon, being useful for diagnosis of machine condition. Raadnui (2019) also investigated wear of gearboxes by analyzing worn surfaces and generated debris, correlating it with lubricant condition and type of contact between meshing teeth. These mechanical systems are usually critical for all industrial processes. The presence of water, acidic components or hard particles could be distinguished, validating the use of wear debris analysis as a tool to find root causes of failures and to improve maintenance actions. Fan et. al. (2017) proposed a model for quantifying wear particles according to the wear rate of the mechanical system, differentiating the running-in, steady state and severe wear conditions. Its application allows verification of machine condition according to its service time without disassembly, since the bathtub curve indicates that high wear rates do not necessarily mean end of life or mechanical problems.

In all these cases the particles were collected from lubricant, whose analysis is one of the most powerful predictive tools. As stated by Behera and Sahoo (2015), fluid analysis for a machine can reveal wear type and severity; worn region; presence and source of contamination in the oil; and changes in chemical and physical properties, indicating if lubricant is still fit for use. Oil undergoes severe degradation mechanisms such as oxidation and temperature degradation, which are accelerated in the presence of external contaminants such as soot, fuel content and water. The resulting sludge mix with wear particles and dust to cause corrosion and severe abrasion of contacting parts in the machine (Campos et. al., 2018). Together with viscosity variation it can cause lubricated components to malfunction or to not operate in its best performance. For instance, Macian et. al. (2016) studied fuel consumption of engines operating with different kinds of oil, revealing that the use of synthetic lubricants could reduce fuel consumption up to 4% due to retaining its low viscosity for a longer time.

Though fluid analysis has high capabilities, it is difficult to determine acceptable variations for its different parameters. Limits for contaminants and degradation of properties vary depending on equipment type and age, operating conditions and user preferences, being specific for each case. Although methods for measuring and analyzing this data follow specific standards, determination of said limits is usually done by OEM, maintenance team through its previous experience, or specialized oil analysis enterprises. It can also be done by analyzing normal values encountered for a numerous sample and applying a mathematical model to it. For instance, Valis et. al. (2015) assumed degradation and wear processes as stochastic and applied linear regression and Wiener method to model evolution of wear particles. They were able to determine Fe and Pb limits for a sample of more than 300 diesel engines. On the other hand, Raposo et. al. (2019) applied a statistical algorithm to extend lifespan of lubricant in a fleet of urban buses, being able to reduce oil changes and increase vehicle availability. The authors analyzed particle quantity and compared to limits determined by a laboratory which are shown in Tab. 1.

Another point worth considering is that postponing oil changes also has environmental benefits. According to Jafari and Hassanpour (2015) a 150 kg barrel of crude oil typically contains less than 2 kg of lubricant-quality based oil. The industrial expansion and global increase in number of vehicles pushes prices upward and demands sustainable solutions such as recycling of oil. This process has an efficiency of about 60% to 75%, meaning approximately 1.6 L of used oil can generate 1.0 L of new lubricant which diminishes usage of raw material.

In this work, lubricant analysis was carried out in different agricultural equipment to verify how predictive methods can identify root causes of failures and impact costs. Although this method has well proven capabilities in improving maintenance practices, Pinto and Nascif (2001) affirms that the cost of monitoring should not be greater than the economy

brought by it. That is why application of this technology in agricultural tractors is fairly recent and still requires further investigation. Oil samples were collected from different compartments and analyzed for contaminants. Results permitted beforehand identification of defects while cost of service and parts was considered to compare economic advantages of the adopted strategy face to traditional preventive and corrective way. Although many works have established models for degradation of lubricant and monitoring methods (Wakiru et. al, 2019), this work innovates in verifying cost feasibility in actual situations. All collected data was obtained through association with a local service provider in agricultural segment and measurements were analyzed according to diagnosis reports provided by a national tribology laboratory.

Table 1. Limits for various diesel engine oil parameters established by an oil analysis laboratory. Adopted from Raposo et. al. (2019).

Characteristics of the oil			Wear and Contamination Metals		
		Limits			Limits
Antifreeze (%)	(PE-TA.071)	0,08	Content in Al (ppm)	(ASTM D-5185-05 mod.)	20
Appearance (dimensionless)	(PE-TA.096)		Content in Cr (ppm)	(ASTM D-5185-05 mod.)	10
Fuel (%)	(PE-TA.071)	4,0	Content in Cu (ppm)	(ASTM D-5185-05 mod.)	35
Water content (%)	(PE-TA.071)	0,2	Content in Fe (ppm)	(ASTM D-5185-05 mod.)	90
Water content (Finacheck) (%)	(PE-5022-Al)	0,2	Content in Mo (ppm)	(ASTM D-5185-05 mod.)	20
Soot (%)	(DIN 51452)	1,5	Content in Na (ppm)	(ASTM D-5185-05 mod.)	40
Nitration (ABS/cm)	(PE-TA.071)	15	Content in Ni (ppm)	(ASTM D-5185-05 mod.)	20
Oxidation (ABS/cm)	(PE-TA.071)	15	Content in Pb (ppm)	(ASTM D-5185-05 mod.)	40
Sulfation (ABS/cm)	(PE-TA.071)	20	Content in Si (ppm)	(ASTM D-5185-05 mod.)	20
TBN (mgr KOH/g)	(ASTM D-2896-07a)	30	Content in Sn (ppm)	(ASTM D-5185-05 mod.)	15
Viscosity at 100°C (cst)	(ASTM D-445-11)	15	Content in V (ppm)	(ASTM D-5185-05 mod.)	00
<hr/>			<hr/>		
Particles		Limits			
PQ Index (Dimensionless)	(PE-5024-Al)	110			

2. METHODOLOGY

Samples and data were collected during after-sale services carried out in the field. Besides strengthening customer relation, it also helps to provide adequate destination for used oil. This is of utmost importance because else way the degraded lubricant might be wrongly discarded, contemning water courses and soil. Jafari and Hassanpour (2015) reveals that 1 L of oil can corrupt 1 000 000 L of drinking water. The appropriate collect not only avoid this but also contributes to oil recycling. Since tens of liters are contained in tractor oil reservoirs being frequently changed, the lubricant recycling chain might collect thousands of liter for a single farm over the course of a year.

Different units of same tractor model used for grain production farms were assessed via lubricant analysis in engine system, final reduction and differential gearbox. This equipment has maximum power and torque of 88 kW and 485 Nm, respectively, supplied by a diesel engine with 6 cylinders and 6.79 L total capacity. Lubricants were collected through a vacuum pump and a single hose and flask were used for each sample. Schematics are shown in Fig. 1a and Fig. 2b shows pump and flask in a photograph. The procedure starts by switching on the machine to allow proper oil circulation, letting it on for about 5 minutes. Compartment is opened and borders are cleaned to avoid contaminations. Hose is then inserted through the opening of the compartment, measuring length of hose to avoid its tip from sucking the slurry at bottom of reservoir. Information related to client, equipment model and unit, compartment, type of oil and hour meter indication were note down in a card and stored together with flasks. Procedure is completed with cleansing of pump.

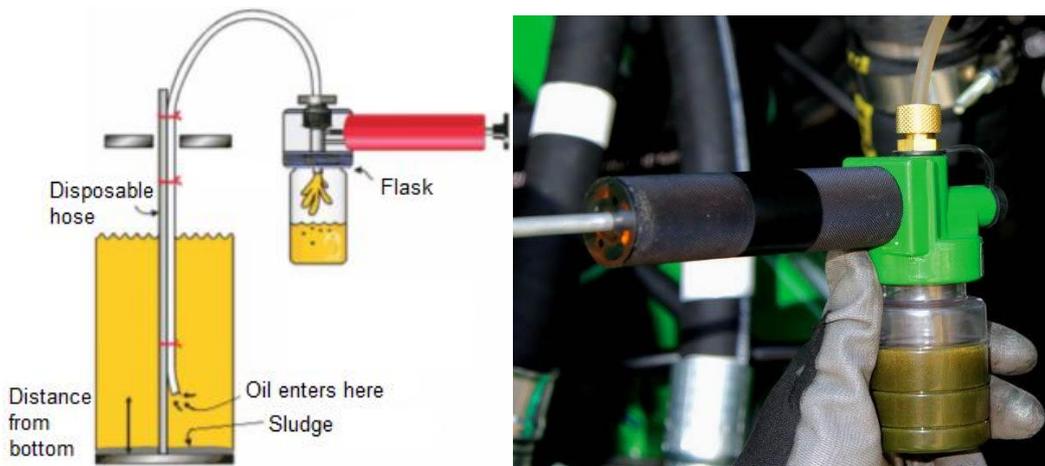


Figure 1. a) Schematics for oil sample collection. b) Actual pump and flask used.

Tests conducted by tribology laboratory follow ASTM and other specific standards (ALS, 2019), but specific limits for contaminant levels and oil characteristics are determined according to laboratory and service provider previous experience. An example of report is given in Fig. 2 which shows all collected data for a set of samples. Although many properties are investigated during a complete oil analysis, monitoring was mainly carried over spectrometric wear debris and contaminants measurement data. Macian et. al. (2003) explains that visible particle counting such as calculated in Particle Quantifier Index – PQI – does not always correlate with actual wear. Besides, spectrometry is the most used method for identifying chemical elements in oil, being usually done with Inductively Coupled Plasma spectrometers. This equipment analyzes photons emitted by material vaporized and excited by a high temperature plasma correlating optical intensity with element concentration. It gives complete chemical composition of particles up to 5 μm . Larger particles are also analyzed within the sample, but are not completely vaporized and therefore have less than 100% recovery. Yet it permits identification of particles generated both in mild and severe wear regimes. The related data was obtained in SpectroGreen ICP-OES analyzer from Spectro Analytical Instruments Inc, in accordance to ASTM D5185. Viscosity tests were run in Trivisc viscometer from Dare Instruments Inc. at 100 °C following ASTM D445, while water content was measured in Karl-Fischer titrator TitroLine 7000 as specified by ASTM E2412-04.

Amostra	Fluido											Dados da Amostra						
	Status	Coleta	Resultado	Horimetro	h amostra	Troca?	Adição											
1800279259	85W140 PETRONAS											Normal	25/01/2019	29/01/2019	1057	1057	Não	
1800171975	85W140 PETRONAS mineral											Normal	04/08/2018	11/08/2018	294	294	Não	
1800028749	85W140 IPIRANGA ULTRAGEAR PREMIUM											Normal	12/04/2018	18/04/2018			Sim	
1700230058	85W140 IPIRANGA Ultragear Premium											Normal	23/11/2017	05/12/2017	3436	202	Sim	
1700169571	85W140 PETROBRAS Lubrax Gold											Normal	13/09/2017	23/09/2017	3024	254	Sim	

Desgaste												Contaminação					Água
Fe (ppm)	Cu (ppm)	Cr (ppm)	Pb (ppm)	Sn (ppm)	Ni (ppm)	Mo (ppm)	Ti (ppm)	V (ppm)	Mn (ppm)	Ag (ppm)	PQI	Si (ppm)	Al (ppm)	Na (ppm)	K (ppm)	Visual.	KF Vol. (ppm)
20	1	0	0	1	0	0	0	0	0	0	11	8	0	0	0		1231
27	2	0	1	1	0	0	0	3	1	0	31	11	3	3	0		1520
8	1	0	0	0	0	0	0	0	0	0	16	4	1	1	0		2125
14	1	0	0	1	0	5	0	2	0	0		3	0	2	0	N	2214
7	0	0	1	0	0	4	0	2	0	0		7	1	5	0	N	2288

Condições do óleo			Carga Aditiva					
Visual	Viscosidade 100°C (cSt)	Oxidação-FTIR (abs/cm-1)	P (ppm)	Zn (ppm)	Ca (ppm)	Mg (ppm)	B (ppm)	Ba (ppm)
Normal	25,19	7	905	6	8	121	240	1
Normal	27,65	6	1337	9	22	736	396	0
Normal	27,67	9	784	5	12	479	262	0
	26,14	10	1441	62	128	870	474	0
	26,27	10	1379	55	123	801	426	0

Figure 2. Example of lubricant analysis report, showing: sample number; type of fluid; sampling info such as date and hour meter indication; wear particles; external contaminants; water presence; oil condition in terms of viscosity, visual aspect and oxidation; additive elements.

3. RESULTS AND DISCUSSION

Acceptable levels of contaminants were established as follows: iron content in the examined engine may be present in up to 50 ppm while for final reduction gearbox and differential gearbox limits are of 150 ppm and 250 ppm, respectively; aluminum and silicon content up to 10 ppm are normal, though 15 ppm is acceptable; water in up to 2000 ppm are plausible. The higher limits observed for gearing systems come from the fact that contact is harsher than in engine and lubricant filtering system is not as sensitive as well. Fe comes from regular wear of contacting internal parts while Al and Si make usually come from dust particles. Some water is always present due to hygroscopic characteristic of lubricant.

Oil sampling followed a predictive maintenance plan in which lubricants were tested every 500 h more or less. Since lubricants are supposedly changed after about 250 h, analysis does not present evolution of lubricant parameters during its use, but only its final condition. Still this information is extremely important because it provides data about fluid compartment and parts that work in contact with oil.

3.1 Engine oil

Figure 3a shows contaminant level and cinematic viscosity for an adequate lubricant. Almost all parameters are within determined limits, except by a small excess of water content in last sample. In Fig. 3b, in the other hand, first point of graph shows extremely high water content of more than 200 000 ppm, which corresponds to more than 20 % of water. This operational condition is highly aggressive to bearings and bushings. As shown by Totten et. al. (2001) any increase of water content decreases bearing lifespan exponentially. The change in oil characteristics was so big that other analysis could not be carried out through standard procedures and readings were not reported by the laboratory.

A consequent inspection exposed that water tank from cooling system was empty. The water line passes through an intercooler where it cools the engine oil, and examination revealed a leakage as the source of contamination. The intercooler and engine oil were substituted and so all parameters returned to normal level. Though tractor had been used in this condition for an unknown period, it did not break down. In case it had, being this the most common consequence, the cost of service and new parts was calculated considering service provider approximate prices for parts such as engine head, rods, piston sets, seals, bearings and bushings. These are shown in Tab. 2 and are compared with cost of changing only the intercooler. As reference, cost of oil analysis is about R\$50 for each sample while tractors cost over R\$200 000.

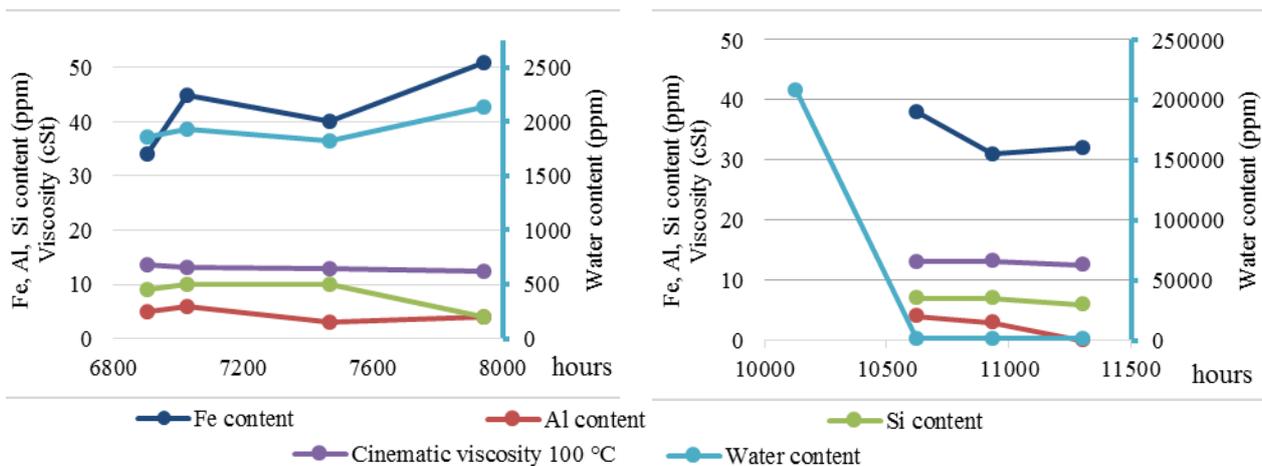


Figure 3. a) Normal engine oil properties. b) Abnormal properties.

Table 2. Comparison of cost between predictive inspection and corrective maintenance for engine.

COSTS	Corrective maintenance	Predictive inspection	Cutback (%)
Parts	R\$35 000.00	R\$1 286.00	96.3
Services	R\$10 000.00	R\$3 252.00	67.5
Total value	R\$45 000.00	R\$4 538.00	89.9

3.2 Final reduction gearbox

Normal parameters for oil of final reduction gearbox are shown in Fig. 4a and are also within limits. Though water content of first sample is an exception, it is acceptable. Figure 4b shows another set in which Fe, Al and Si content are above limits. High iron content is due to wear of steel gears and bearings, which is enhanced by the presence of hard particles such aluminum and silicon oxides coming from dust.

This gearbox is arranged in a way that oil does not contact or circulate through any other system and the equipment's own weight helps to keep the necessary pressure in seals to avoid entrance of any dirt or water. In this case, contamination is prone to happen during oil change operation. The process requires tractor driver to open the compartment with opening at 12 o'clock position and then move the tractor slightly forward, only enough for oil to spill through a second opening, revealing oil level. Water and dirt or dust might enter the compartment if operators do not clean the wheel properly. Once oil is changed, contaminant level decreases, but some of it remains attached at internal surfaces and levels might continue above limits. The content tends to decrease to normal values in following lubricant changes. This shows importance of training employees to execute maintenance properly, or paying for a certified service alternatively. Table 3 compares cost of oil change service from local provider with cost of repairing all gearbox set, indicating how expensive corrective maintenance could be. Gearbox set comprehends spacers, flange, bushings, pinion, pins and pressure rings. This comparison does not even consider consequential losses like production stop or fines from breaking supply contracts and deadlines.

Table 3. Comparison of cost between predictive inspection and corrective maintenance for final reduction gearbox.

COSTS	Corrective maintenance	Predictive maintenance	Cutback (%)
Parts	R\$8 000.00	no parts required	100.0
Services	R\$3 500.00	R\$300.00	91.4
Total value	R\$11 500.00	R\$300.00	97.4

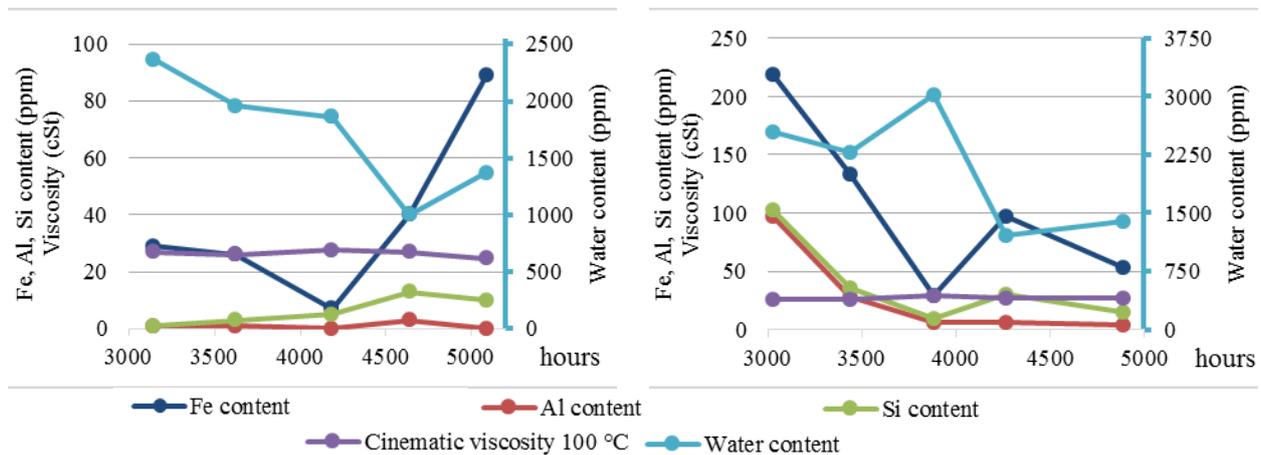


Figure 4. a) Usual values for viscosity and contaminants in final reduction gearbox. b) Unusual contaminant levels.

3.3 Front differential gearbox

Figure 5a shows normal values for iron, aluminum and silicon content and cinematic viscosity at 100 °C. Water content is above expected level in first measurements, but is still acceptable. In other equipment the results from first analysis were abnormal for Fe content and viscosity, as shown in Fig. 5b. In the case of the later, the actual reason is unknown but there is a strong possibility that engine oil was used for completion or during change, since obtained viscosity values are close. In case of iron content, it is related to low oil level verified during oil maintenance. This caused gears to engage unlubricated, inducing severe metal-to-metal contact where high tensions generated metal debris. This was confirmed by PQI (Particle Quantifier Index) of report analysis, which indicates quantity of visible particles. Values of 334 and 776 were obtained for fourth and fifth tests, while in the other measurements there were no visible particles.

Low level was caused due to leakages in one of the seals, which was confirmed by adhered dirt to bottom external surface of differential gearbox. Defective seal was substituted and lubricant was replaced, and so parameters came to expected levels. Cost of repairing seals were compared with cost of completely replacing a broken differential gearbox and are shown in Tab. 4. It is usually required of the client to replace all components of the set by new parts, because in assemblies of new and old parts together there will be clearances and poor seating of parts, causing premature wear and soon demanding service to be redone. Set consists of bearings, seals, bushings, screws, chocks and differential gears. Again, predictive approach presented substantial economic advantage.

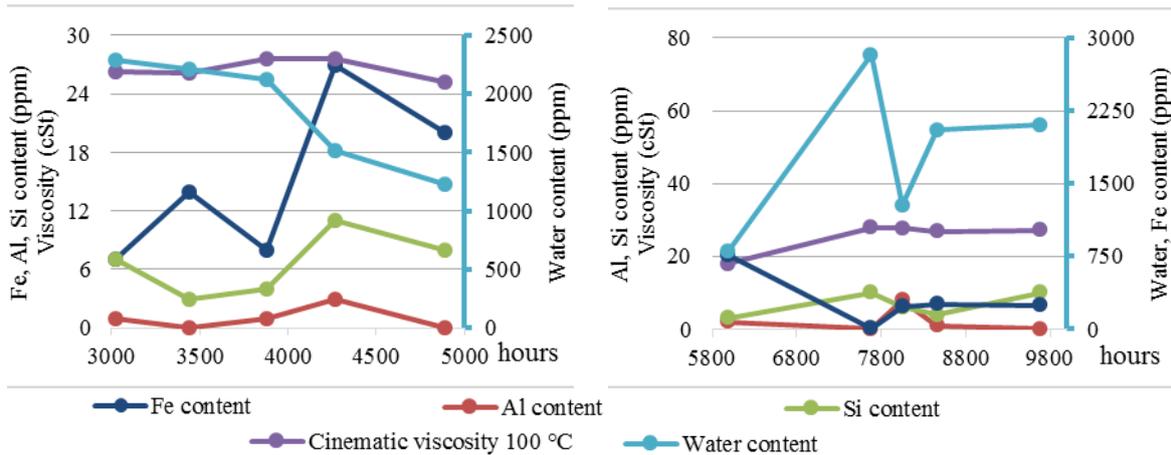


Figure 5. a) Characteristics of oil from regular front differential gearbox. b) Lubricant parameters in defective gearbox.

Table 4. Comparison of cost between predictive inspection and corrective maintenance for front differential gearbox.

COSTS	Corrective maintenance	Predictive maintenance	Cutback (%)
Parts	R\$15 000.00	R\$500.00	96.7
Services	R\$6 000.00	R\$1 400.00	76.7
Total value	R\$21 000.00	R\$1 900.00	91.0

4. CONCLUSIONS

Predictive maintenance of tractors was incorporated to after sale service of a local enterprise in agricultural segment. Oil analysis was used as a tool to assess engine and gearboxes conditions, evaluating viscosity, wear particles and contaminants such as iron, aluminum, silicon and water. Except by water and viscosity measurements, particle were identified and quantified via Induced Coupled Plasma spectrometry. Data for different equipment was compared to acceptable limits determined by oil analysis laboratory and own maintenance team. Specific cases were used as example of how this strategy can be used to diagnose problems and find root causes, avoiding breakdown of equipment and guaranteeing its availability during harvesting periods.

In first example, extremely high water content in engine oil led to discover of a leakage in oil heat exchanger. Continued use in previous condition would cause engine complete failure which costs 10 times more than fixing the oil intercooler. Elevated Al and Si content in oil led to higher wear of final reduction gearbox in second case. The probable cause was determined as contamination by dust during oil change procedure which justifies paying for certified service, once it costs less than 3% of a new gearbox set. In third example, low oil level and iron content revealed defective seals, for which parts and service costs less than 10% of replacing differential set by a new one.

In all of this cases, lack of predictive maintenance would lead to catastrophic wear and sudden failure of equipment. Besides greater spending with service and parts, loss of profit, wastage of products and potential fines from breaking deadlines would be much higher without predictive maintenance, justifying feasibility of this method for agriculturist. It is important to highlight though that these percentage cutbacks do not represent total savings for all machinery when implementing predictive maintenance over corrective. It has been reported by the local service provider that about only 3 in each 10 analysis reveal a critical situation, which could mean in a certain way that the other 7 did not bring any savings but only costs. Therefore, total cutbacks for an entire fleet would be significantly smaller.

From an environmental point of view the use of certified service guarantees proper discard of used lubricant and then contributes to oil recycling. In some farms where service is not carried out by specialized labor, oil might not be properly disposed of due to lack of supporting logistics or even unawareness of oil contamination potential.

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6. RESPONSIBILITY NOTICE

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