COSTS ANALYSIS BETWEEN PREDICTIVE AND CORRECTIVE MAINTENANCE FOR AN AGRIBUSINESS MACHINE

Leonardo Rosa Ribeiro da Silva
leonardo.rss@gmail.com
Gustavo Henrique Nazareno Fernandes
ghnfernandes@gmail.com
Felipe dos Anjos Rodrigues Campos
filipin_anjos@hotmail.com
Pedro Henrique Pires França
pedrohenriquepiresf96@gmail.com
Luiz Eduardo Rodrigues Vieira
luizeduardoodrigues@gmail.com
Felipe Chagas Rodrigues de Souza
felipechagaslepu@gmail.com
Augusto César Santos Peixoto
augusto-csp@hotmail.com

Universidade Federal de Uberlândia – 2121, João Naves de Avila Avenue, Laboratório de Ensino e Pesquisa em Usinagem, 1º block – Uberlândia, Brazil

Abstract. *In this work, it was analysed a real situation where Predictive Maintenance -PDM strategy was applied for a sugarcane agribusiness tractor. This machine was operating under severe working conditions, 24 hours daily, directly in contact with dust, earth, stones, and so forth. The PDM was performed periodically (500 hrs. interval), measuring many parameters such as Compression Rate - CR, used as a reference here. To verify diesel engine conditions, it was used a manometer, brand Planatc, model MC-2000, to measure CR of the engine six cylinders. In one of the inspections, it was noticed a low CR in cylinder 6, overloading parallel cylinder 1, leading to immediate machine stop and corrective maintenance, in order to avoid damages accumulation. A Failure Mode and Effect Analysis to discovery root problem noticed that the primary filtering element was broken, allowing impurities to enter the engine system. After services performed, PDM total costs were stipulated and compared to a hypothetical situation where the machine had had to be kept running until failure, then having to do a Corrective Unscheduled Maintenance - CUM. The analysis showed PDM to be a much better-chosen strategy. The cost-benefit ratio was estimated in about ~10x, disregarding the losses of stopped machine time: 2 days for PDM and 10 days for CUM.*

Keywords: predictive maintenance, corrective maintenance, costs, agribusiness.

1. INTRODUCTION

Agricultural production is one of the most profitable economic sectors in Brazil. Cazetta (2018) says that only in 2017, it was responsible for ~ 24% of the entire Brazilian GDP – Gros Domestic Product. One problem of this field is that it is too unpredictable, where the value of the final product varies regularly depending both of external and internal factors, considering: commodities established price in the international market, political commerce agreements, logistics, climate conditions, etc.

In order to mitigate the effects of unpredictability and optimise business profits, harvesting processes must be well planned. For this, the financial planning includes forecasts, per hectare ($10,000m^2$), of calculation of grain, the number of fertilisers, pesticides, among others. Another factor to be considered is the availability of agricultural machinery. These machines are the most expensive durable resources among those needed for agricultural production, and a critical factor in the harvesting process. Failure of these equipment can turn the harvest flow unfeasible generating significant losses, according to de Jesus Ribeiro (2004)

During the harvest period, farmers in a given region use their machinery at the same time and in high demand. Rain, or even high humidity, can interrupt the process. In the case of grains, moisture prevents the grain from separating from the comb, causing wastes. In other crops, such as sugar cane, moisture prevents the separation of straw and cane, clogging compartments of the harvester. So, in order to avoid problems like these, it is necessary to produce as much as possible, generally within a short period. Consequently, machines are subjected to many unexpected failures, generating a high demand for maintenance services that in many cases cannot be fulfilled in a reasonable time, due to lack of labour, parts, etc.

Machinery used in agribusiness generally is subject to severe use. Silva (2018) explain that these machines operate in environments with excessive dust, earth, stones, vegetation, woods, water, etc. These elements then become a source of contamination that can affect components and damage it. A widespread failure that occurs is the lack of lubrification since the dust with earth acts over the lubricant system affecting its capacity inserting abrasive particles. For instance, the simple loss of lubricity in a bearing can difficult the machine movement, causing an overload in the engine that would have to operate in a higher rotation level. This could elevate the system temperature, and in a continuous operation, the scenario could cause damage to other expensive components. Another common failure occurs in the filtering system when tractors move over ground raising a big cloud of dust, branches, stones, etc. that can overload the capacity of filtering elements or even breaking pieces causing contamination in the subsequent systems, just like in the engine, turbine, as studied by Needelman and Madhavan (1988).

Maintenance development methods came helping to avoid a situation like this. In Kardec and Nascif (2009) maintenance is divided into six different strategies: Corrective Unscheduled Maintenance - CUM, Corrective Schedule Maintenance - CSM, PreVentive Maintenance - PVM, PreDictive Maintenance - PDM, Detective Maintenance - DM and Maintenance Engineering - ME. The corrective one consists of repairing equipment when it failures. This correction can occur in two different ways when scheduled or unscheduled. Generally, when the failed component is crucial for the system correct operation, it is necessary to apply a CUM. Monteiro, Souza & Rossi (2010) explain that when a machine can be kept running without any other concerns, CSM can be done.

Dhillon (2002) describes the second way of maintenance: the preventive one. This methodology, when well-applied, consists of using statistical analysis of the component to obtain its useful life, based on the time of hours that it can run without any issue. So, the component repair or changing can be previously scheduled. The advantage of PVM is that it can avoid unexpected failures. However, the change is based not in the real material state, so it is not optimal, affecting costs. Another disadvantage is that the component can fail before its estimated number of hours, causing a CUM or can be changed prematurely, causing inherent loss. The interval of maintenance is generally given by manufacturers using statistical methods having a security factor associated.

Jardine et al. (2006) explain that predictive maintenance consists of keeping analysing the useful life of a component to verify its working conditions. This analysis can be performed in real time or periodically. Generally, real-time inspections are more reliable. However, its costs are more expensive when compared to the periodic one. In the PDM, the chances of the component to failure abruptly are dramatically reduced. It also helps to optimise the piece usage, getting the maximum of its useful life, consequentially reducing costs. When it is noticed that the equipment need repair, the preventive maintenance can be scheduled, as stated in Pereira & Neves (2000).

In Kardec and Nascif (2009), another kind of maintenance is explained: detective one. The author describes this method as: *"an action over the protection systems looking for potential hidden failures not noticeable by operators or maintainers."* This procedure generally involves complex activities, especially when dealing with more sophisticated systems and must be done by skilled maintainers, preferentially accompanied by operators. Tasks like this can take long hours and significant times and almost ever need to be done with the machine stopped.

Finally, Kardec and Nascif (2009) state the Maintenance Engineering - ME as a more sophisticated strategy that covers all the other ones and even more. The main idea of this technique does not only keep doing maintenance but keep looking for improvements that can be done to avoid future failures. To well practice ME it is necessary to have a dedicated structure with high qualified team workers and a company committed to cultural changes. More modern management techniques talk about, instead of having a cultural changing, having a changing culture. So, ME also needs a well-established design methodology to be applied. This practice can bring high economic, security and even environmental results for companies when correctly performed. Table 1 shows the average associated costs by maintenance type versus horsepower used.

Table 1. Maintenance Method and associated costs by installed power (Kardec and Nascif, 2009)

Maintenance Method	Costs US$/HP/year
Corrective unscheduled	17 to 18
Preventive	11 to 13
Predictive and condition monitoring/corrective scheduled	7 to 9

Many papers have been published about this subject comparing different maintenance methods. Silva (2018) used predictive maintenance by fluids analysis to investigate the behaviour in agricultural tractors. He concluded that using the results obtained through fluid analysis; it is possible to anticipated components failure, such as breaking gears, cast motors, damaged transmissions, leaks in hydraulic systems, etc. Costa, Andrade, and Caetano (2015) used this methodology in a fleet of agricultural machinery during offseason in order to maximise the availability of the machines avoiding stops by unexpected failures. The results were positive, and there was a reduction in losses.

Nilsson and Bertling (2007) analysed wind power Life Cycle Cost – LCC to verify the profitable when using a Condition Monitoring System (CMS). It is maintenance management that consists of continuously monitoring the performance of wind turbine parts. They compared two case studies, one single wind turbine onshore and a wind farm offshore. The authors could conclude that for a single turbine, the costs of CMS are not justified. However, for the entire farm, condition monitoring system costs would be justified.

Cerveira and Sellitto (2015) used the method of Reliability-Centered Maintenance - RCM to do a quantitative analysis of an electric induction oven to determine which maintenance strategy would be better to be applied. The standard SAE-JA1011 defines RCM as: *"is a specific process used to identify the policies which must be implemented to manage the failure modes which could cause the functional failure of any physical asset in a given operating context."* In other words, it is a management tool that was initially developed by the USA aeronautic industry supported the logical concept of total security, i.e., any component, equipment or system has an intrinsic reliability associated, so, techniques (maintenance methods, failure mode, and effect analysis, etc.) must be applied to assure that reliability. In numbers, if the change of a plane turbine to fail is zero, or near to zero, RCM must be applied in the entire product concept to assure this reliability. In the work of Cerveira and Sellitto (2015), after applying RCM, analysing Time Between Failure – TBF, availability, time to repair, among other concepts, they could conclude that the predictive maintenance strategy would be better for their studied case.

Singh et al. (2013) studied the effects of implementing Total Productive Maintenance – TPM in a machine workshop having a CNC turning as object of study. This tool was first implemented in 1971 by Seiichi Nakajima in Japan by a Toyota subsidiary company, Nippon Denso KK. The Total Productive Maintenance is another kind of management tool focused on improving Overall Equipment Effectiveness (OEE). The idea is that the machine cannot stop during the time it was programmed to be running. For reaching this goal, TPM is constituted above eight pillars: free maintenance focused improvement, planned maintenance, quality management, early/equipment management, education and training administrative & office TPM, safety health environment. Singh et al. (2013) after applying the TPM concept could improve the CNC OEE from 63% to 79%. They eliminated the non-planned maintenance, passing to use preventive and predictive strategies. Table 2 summarises thirteen observed indexes before and after TPM implementation.

Table 2. Maintenance Method and associated costs by installed power Singh et al. (2013)

Sr. No.	Category	Before TPM	After TPM
1	Shift time	720 min	720 min
2	Total production in a shift	160 Nos.	72 Nos.
3	Scheduled break	50 min	50 min
4	Non-scheduled break	5 min	0 min
5	Breakdown	4 min	0 min
6	Cleaning, inspecting & tightening of the insert	15 min	15 min
7	Operator absent	55 min	6.5 min
8	Non-conforming product	5 Nos.	3 Nos.
9	Theoretical Cycle Time	3 min	7.5 min
10	Availability *(A)*	0.90	0.98
11	Performance Efficiency *(PE)*	0.73	0.85
12	Quality Rate *(QR)*	0.96	0.95
13	OEE *(A x PE x QR)*	0.63	0.79

Rodrigues et al. (2017) used a PDCA – Plan-Do-Check-Act methodology to verify the quality improvements that could be done to obtain a gain of productivity in maintenance activities, more specifically in the use of internal coating (Chock Bar) in the application of Shuts of a conveyor belt. The problem was that the mineral ore wears the shuts, many times causing CUM. They used the PDCA and could verify the leading causes of the problem were (Rodrigues et al., 2017): *"Shuts-related failures occurred mainly at points where there was continuous friction of the material causing cracking, structural conditions, wear conditions, cracks and wear plate fixation, bore holes in the walls, increased wear on contact points, cracks, and even small cuts"*. They applied maintenance engineering concepts and gave a solution to unexpected failures. They used coated plates in the transportation system. These plates have good wear resistant, so, the number of CUM was drastically reduced, passing to PDM.

Stenström et al. (2016) made a comparison between preventive and corrective maintenance costs to verify the cost-benefit of both. For doing that, they analysed historical maintenance data of 7 railway lines having 65 sections. In their work, they considered many factors that affect the financial balance of this analysis, including direct and indirect costs. In maintenance services, direct costs are those strictly associated with the equipment repair; basically, materials and labour and indirect cost are the other ones. They concluded that, for using PVM, instead of CUM, the cost-benefit ratio was estimated at 3.3, with results highly dependent on the input data (Stenström et al., 2016).

Ribeiro and Gomes (2016) did a review of the predictive maintenance strategy to analyse internal combustion engines. They presented in their work many techniques of analysing parameters that indicate the engines working quality, among them (Ribeiro and Gomes, 2016):

- Acoustic emission; consist of monitoring and analysing the engine by its working sound. When working the engine emits a lot of mechanical waves in the form of sound that can be measured and compared to standards parameters;
- Lubrication oil analysis; this technique involves taking a sample of the engine oil and verifying its composition, physical-chemical properties, presence of particles, etc.

- Vibrational analysis; consist of measuring the level of vibration generally using accelerometers. Frequency analysis is commonly used to verify the parameters of good engine condition.

One possible parameter that can be measured to do a PDM is the compression rate in an engine. One advantage of the compression test is that it requires relatively simple instrumentation to be installed and can be performed *in loco*. Another favourable point is that the measurement can be made immediately to the data collection, not depending on analyses by laboratories or specialists. The ideal compression range is predetermined by the manufacturer, as well as possible causes and solutions for values out of order.

The compression rate can be measured in two ways: directly, using a manometer, or indirectly, using a pressure sensor that store data in the machine CPU. In the case of indirect measurement, generally a computer (laptop) is connected to the machine's Central Processing Unit - CPU, so it is possible to perform the test and generate a report containing the CR as function of working time. The advantage of this method is that it is carried out in a few minutes and does not require disassembly of parts. One disadvantage is that the measurand is not too accurate because it is taken indirectly through an association with the gases from the exhaustion system. In the case of direct measurement, a manometer is inserted in the place of the nozzle for each cylinder. When attempting to start ignition, the inlet fuel-air mixture will gradually raise the pressure in the cylinder, and when stabilising, the gauge registers its compression.

Kumar et al. (2016) did a *"Performance evaluation and emission analysis of variable compression ratio direct injection diesel engine."* For doing that they used a single cylinder, four strokes, water cooled, direct injection, variable compression rate designed to develop a rated power of 3.5 kW at 1500 rpm. They used CR (ranging from 18 to 22 MPa) varying its load to associate with engine performance. To measure engine exhaust gases, it was used two analysers: AVL DIGAS 444 exhaust gas analyser and AVL DITEST CDS 450. Compression rate could be varied using adjustors based on tiling the cylinder block of the engine. One of their conclusions is that: "*compression ratio 21 is giving maximum Brake thermal efficiency at the part as well as a full load. Brake specific fuel consumption and Brake specific energy consumption is found minimum at compression ratio 21* (Kumar et al., 2016).

In this work, it was analysed a real situation where Predictive Maintenance -PDM strategy was applied for a sugarcane agribusiness tractor with diesel engine tractor, where the main goal is to analyse two maintenance strategies and financially compare both. For this, PDM total values were stipulated and compared to a hypothetical situation where the machine had had to be kept running until failure, then having to do a Corrective Unscheduled Maintenance - CUM.

2. EXPERIMENTAL PROCEDURES

2.1 MATERIALS & EQUIPMENTS

The maintenance in agricultural machinery is like that of passenger cars: oil / fluid exchange, filters, alignment, and balancing. One difference is in the so-called "industrial part" which is the specific function of each agricultural machine. They are usually driven by hydraulic pumps, which are parasitic loads of the diesel engine that drives the machine. Figure 1 shows an example of the tractor machine analysed in this work. The diesel engine was the main component analysed, which main specifications are shown in Table 3.

Figure 1. Example of tractor used in the agribusiness.

It was adopted as a direct CR measurement method made *in loco*. It was used a manometer, brand PLANATC, model MCD-2000, nominal range 0 to 70 kgf/cm^2 (6.86 MPa), resolution 1 kgf/cm^2 (98 KPa). This manometer has a calibration curve that is given by the Eq. 1, and is strictly dependent on the local altitude where this instrument is going to work:

$$R_2 = R_1 * [1 - 1,2 * 10^{-4}(A_2 - A_1)] \tag{1}$$

Where: $R1$, Compression range set by the manufacturer [MPa];
$R2$, Compression range limit for the new region where compression gauging will be performed [MPa];
$A1$ Region Altitude, where the machine was manufactured [m];
$A2$ Region Altitude, where reduction is measured [m].

The manometers used was manufactured in a region with an altitude of 183 meters and had its compression interval defined by the manufacturer between 24 to 28 MPa. Measurements were performed in Uberlândia city (Brazil), whose altitude is 887 meters. Using equation Eq. 1, it was possible to calc intervals being approximately 22 to 26 MPa.

Table 3. Diesel engine specifications of tractor analysed

Engine type	6068HL280
Maximum engine power	88 kW
Maximum torque	485 N.m for 1600 rpm
Number of cylinders	6
Diameter of cylinder	106.5 mm
Piston length	127.0 mm
Displacement	6 790 cm^3
Ignition order	1-5-3-6-2-4
Clearance at the intake valves	0.36 mm
Clearance at exhaust valves	0.46 mm
Slow running	850 rpm
Accelerated march	2 460 rpm
Engine nominal rotation	2 300 rpm
Operational speed range	1 600 a 2 300 rpm
Engine speed for rear TDP in 540 rpm	2 124 rpm
Engine speed for rear TDP rear in 540 rpm (reversible)	2 143 rpm
Engine speed for rear TDP rear in 1000 rpm	2 208 rpm

2.2 METHODOLOGY

It was used periodic predictive maintenance with an interval of 500 h, determinate by manufacturer, between each CR measurement. It is essential to highlight that during this period, many situations can occur that can affect working conditions. The methodology adopted is strictly dependent on CR measurements. Table 4 contents the manufacture CR nominal range (Deere, 2015).

Table 4. Normal compression rate in good operation conditions. (Deere, 2015)

Compression Rate (CR) test [MPa]	Specifications [MPa]	
	Minimum	Maximum
Cylinder 1	22	26
Cylinder 2	22	26
Cylinder 3	22	26
Cylinder 4	22	26
Cylinder 5	22	26
Cylinder 6	22	26

Another variable important to analyse is the *Relative Compression Rate – RCR*. This parameter is measured about the other measurements of CR, given by Equation 2:

$$RCR = \frac{CR_1^6}{CR_{max}} \, x \, 100 \, [\%]$$
(2)

Where: CR is the compression rate varying from cylinder 1 to 6;
CR_{max} is the maximum compression rate of cylinders 1 to 6.

For example, considering six cylinders, if cylinder 1 has the higher value (CR of 24 MPa), this is normalised as being 100%, and all other values are correlated to this one, being a percentage. So, if Cylinder 2 has 23 MPa, its *RCR* is ~96%. The RCR is essential to verify because a deviation above 10% indicates that there is an unbalance of loads inside the engine, leading to a stress effort of the other cylinders to compensate the power of that defective one (Deere, 2015).

Then, according to manufacturer instructions, the engine diagnosis is made accordingly to two parameters, CR and RCR (Deere, 2015) . To make a diagnosis of the values measured, there are four (2^2) possibilities of results combined of two variables, CR and Relative Compression Rate (10%). One other possibility is $CR > 26 \, MPa$; however,

this situation is rare to happen and its simple to solve, generally just involving some adjustments, so it will be discarded for this analysis. Table 5 shows the diagnosis possibilities:

Table 5. Diagnosis of Diesel Engine measuring CR and calculating RCR

Condition Nº	Compression Rate Measured (MPa)	Relative Compression Rate (%)	Diagnosis
1	22 < CR < 26	RCR <10%	Ok
2	22 < CR < 26	RCR >10%	CUM
3	CR* < 22	RCR <10%	Ok with CSM
4	CR < 22	RCR >10%	CUM
* Conditional situation: If all the six cylinders have CR < 22 MPa, automatically needs CUM, independently of RCR			
Obs.: When CR > 26 MPa it is necessary an adjustment of valves or excess in lubricant oil, in this case, a CSM is indicated			

During the useful life of the tractor, its familiar to CR keeps dowsing due to the inevitable wear of moving parts, shown in Figure 2.
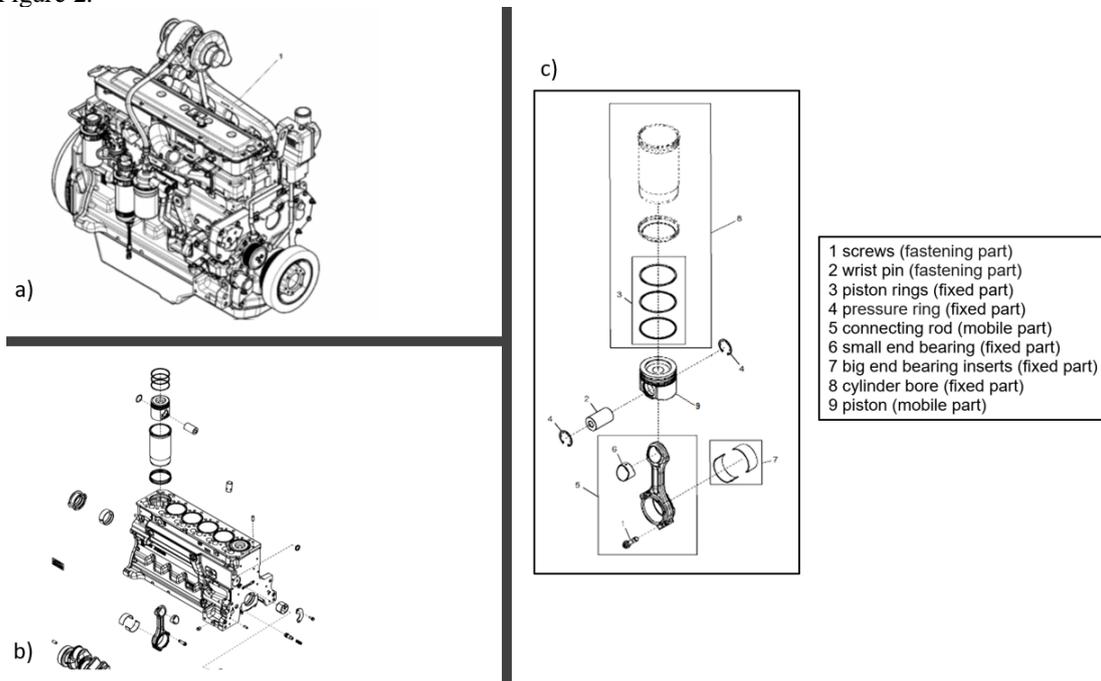

Figure 2. a) Diesel Engine *88 kW (120 hp); b)* disassembled engine block;
c) Fastening and fixed parts of the diesel engine *88 kW (120 hp)*

All the CR tests were performed with the engine at working temperature and taken in the compression engine phase. The cold engine has gaps (in the rings and piston) that leave the compression poor. When they reach the working temperature, these gaps are eliminated due to thermal expansion. A deviation was noticed, so corrective maintenance was scheduled. Following the basis of the Maintenance Engineering, a FMEA – Failure Mode and Effect Analysis was performed intending to discover the root cause of the problem.

The total maintenance cost was analysed in this case (Predictive Maintenance), and it was compared with a hypothetical situation where this machine would be kept running until failure. The values were then compared and discussed as follows.

3. RESULTS AND ANALYSIS

3.1 ANALYSIS OF COMPRESSION RATE

Table 6 shows the results of CR measurement. This means that Cylinder 2 is referential. All the other measures are a percentage in comparison with this other one. The tests indicate that the engine had a critical failure in cylinder 6. The *Relative Compression Rate - RCR* of cylinder 6 was above 18%, indicating that this component was not working correctly, overloading cylinder 1 that is in parallel with this one (Deere, 2015). This situation falls under condition 4 (Tab. 5) and requires an immediate stop of the tractor to avoid damage accumulation. In this case, a Corrective Maintenance is required.

Table 6. Results of compression rate measured with a manometer

Compression Rate Analysis	Specification (MPa)		Results (MPa)	RCR (%)
	Minimum	Maximum		
Cylinder 1	22	26	20,5	91%
Cylinder 2	22	26	22,5	100%
Cylinder 3	22	26	21,5	96%
Cylinder 4	22	26	21,5	96%
Cylinder 5	22	26	21,5	96%
Cylinder 6	22	26	18,5	82%

The engine was disassembled, and the cylinder 1 and 6 were submitted to analysis. A FMEA was done in order to discover the root cause of the compression rate loss. A logical sequence of actions was taken. It was verified the mainly possible causes of decompression: 1) the sealing cylinder rings was verified. It was okay; 2) the piston was verified if it had not melted; It was okay 3) it was verified whether the connecting rod had warped. It was okay; 4) it was verified whether the bronzin was at the end of its useful life. It was okay. Finally, it was verified by visual inspection that cylinder 1 and 6, had earth presence, as shown in Fig. 3 and Fig. 4.

Figure 3. The top surface of Cylinder 1 (left) and Cylinder 6 (Right), both with the carbonised crust.
An indicative of earth in the combustion chamber

The top and lateral carbonised crust in both cylinders, 1 and 6, is a strong indicator of a failure in the filtering system. What generally happens is that the significant volume of dust raised by the tractor gets inside the engine compartment and are aspirated into the system. The filter element must be changed after 100 h of working. However, it is known that in a rural environment is challenging to measure this time, and sometimes due to machine demand, this factor is ignored. Figure 5) shows that the filter element was broken.

Figure 4. Lateral surface of Cylinder 1 (left) and Cylinder 6 (Right), both with carbonized crust.
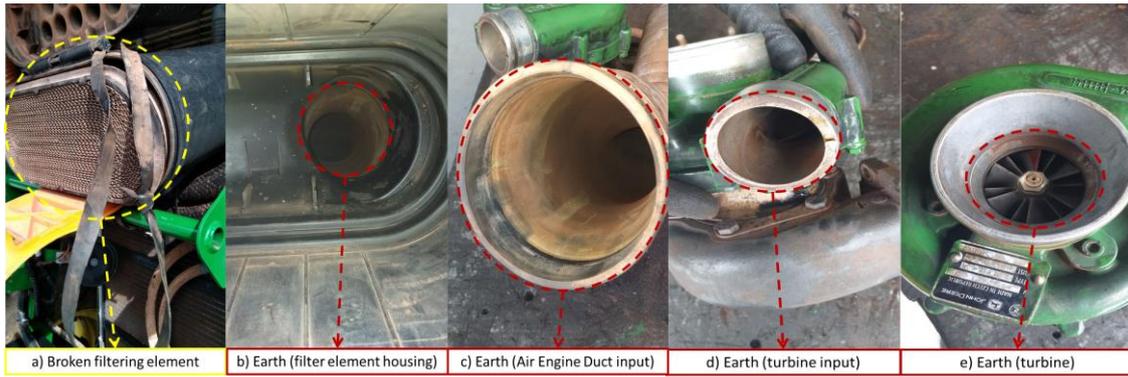An indicative of earth in the combustion chamber

Figure 5. FMEA analysis showing root cause of compression rate loss problems.

3.2 ANALYSIS OF MAINTENANCE COSTS: PREDICTIVE X CORRECTIVE

Analysing the possible failures that can occur due to the problem in the filtering system, it was established a cost relation for the two kind of maintenances here, PRD and CUM. The Eq. 3 shows an equation relating problems:

$$C = a * X + \sum_{i=0}^{b} Y_i + c * Z \tag{3}$$

Where: C total cost [dollar],
a labor time [hour],
b number of parts,
c downtime [day],
X labor cost [dollar /hour],
Y_i parts cost and other [dollar],
Z downtime cost [dollar/hour],

In the case studied, a dealer authorised by the manufacturer was consulted. The following values were provided for the variables: The labour cost is $ 55 per hour. The parts to make the necessary repairs vary in each situation. The value of the downtime varies for each type of client and its own enterprise.

3.2.1 PREDICTIVE MAINTENANCE COST

The PDM was composed by using the Equation (3), using the following values:

- **Parts cost:** those required to replace the engine head seal: $ 250.
- **Services:** labour inspection for what led to the discovery of the problem: $ 250.
- **Machine idle time:** 1 day for the inspection and transportation of parts and 1 day for the execution of the parts exchange.
- **Repair time:** 15 hours

$$C = a * X + \Sigma Y_i + b * Z \tag{4}$$
$$C = 15 * 55 + \Sigma(250 + 250) + 2 * Z$$
$$C = 825 + 500 + 2Z$$
$$C = 1325 + 2Z \text{ [dollar]}$$

3.2.2 CORRECTIVE MAINTENANCE COST

The CUM was composed by using the Equation (3), using the following values:

- **Parts cost:** those required to replace the engine head seal: $ 250.
- **Services:** labour inspection for what led to the discovery of the problem: $ 250.
- **Machine idle time:** 1 day for the inspection and transportation of parts and 1 day for the execution of the parts exchange.
- **Repair time:** 15 hours

$$C = a * X + \Sigma Y_i + b * Z \qquad (5)$$
$$C = 48 * 55 + 10000 + 10 * Z$$
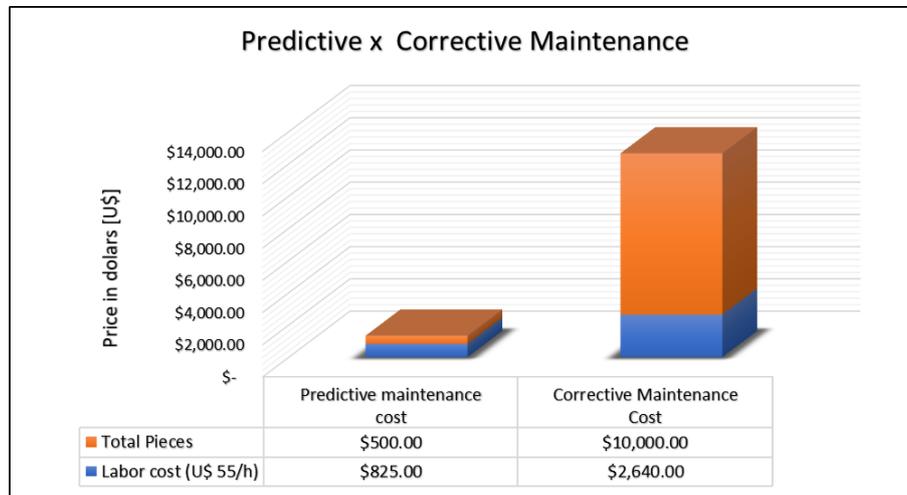$$C = 2640 + 10000 + 10Z$$
$$C = 12640 + 10Z \text{ [dollar]}$$

Figure 6. Predictive x Corrective Maintenance cost comparison

Figure 6 shows a comparison graph with the total costs of predictive x corrective maintenance. It is observed that the difference in costs is about 10x more with corrective unscheduled maintenance. This is a typical situation that proves the advantage of using more sophisticated strategies methods. When the machine is kept running until failure, the accumulated damage is much more pronounced. For the tractor analysed here, it would mean complete damage to the diesel engine, causing costs to be much more expensive. Another consideration is that the loss while the machine was stopped were ignored since this situation depends on more complex analysis and the kind of business that the machine executes. For this work, the total stopped time for PDM was 2 days and for CUM 10 days.

4. CONCLUSIONS

In this work, it was performed a study case of a tractor used in agribusiness. The tractor diesel engine was under periodic predictive maintenance with an interval of 500 hrs. At each inspection, the compression rate was measured with manometers, and in one of the values found a deviation of normalised manufacturer parameters.

After the engine disassembled, it was verified the presence of earth in top superficies of cylinders 1 and 6. A FMEA – Failure Mode and Effect Analysis was performed intending to discover the root cause of the problem. It was noticed that the primary filtering element was broken. This was allowing the passage of dust with the earth through the system. Earth was found in many components, just as: filtering element housing, engine and turbine input air systems and inside the turbine.

The corrective maintenance (after predictive) was performed with the total cost estimated in about U$ 1 325.00. An essential part of the cost, that associated with the loss with the machine stopped could not be measured, because it was a sensitive data of the client business. However, the stopped time to perform correction was 2 days.

The theoretical corrective unscheduled maintenance cost was estimated too if the machine had had to be kept working until total engine failure. In this scenario, the cost to repair the engine would be around U$ 12 640.00. Almost ten times higher than using predictive maintenance strategy. This cost is probably much higher since the machine would have to be stopped around 10 days to perform the correction. However, it could not be determined.

It was possible to verify that use proactive maintenance is affordable in the use of big equipment just like the case in this work, a tractor agribusiness. Costs analysis demonstrated that using PDM is much more competitive than waiting for the machine to break to do maintenance then. Even cost analysis being hampered by the fact that there were no machine-hour losses, for this study scenario, it is possible to assure the advantages of PDM.

5. ACKNOWLEDGEMENTS

6. REFERENCES

Cerveira, D.S., Sellitto, M.A.J.R.P.O., 2015. Manutenção centrada em confiabilidade (MCC): análise quantitativa de um forno elétrico a indução. 15, 405-432.

De jesus ribeiro, O.D.J.R.E.d.C., 2004. Adequação dos custos da atividade agrícola. 1, 225.

Dhillon, B.S., 2002. Engineering maintenance: a modern approach. Crc press.

Jardine, A.K., Lin, D., Banjevic, D.J.M.s., processing, s., 2006. A review on machinery diagnostics and prognostics implementing condition-based maintenance. 20, 1483-1510.

John Deere. Manual Técnico de Diagnóstico - Teste da Pressão de Compressão do Cilindro. Montenegro: John Deere, 2015. 2 p. Disponível em: <serviceadvisor.deere.com/WebSA/manuals/tm803254/09001faa80fceb15>. Acesso em: 13 maio 2019.

Kardec, A., Nascif, J., 2009. Manutenção-função estratégica. *Qualitymark Editora Ltda.*

Kumar, N., Soni, S.L., Sharma, D., Srivastava, A.K.J.M.I.J.o.S., Technology, 2016. Performance Evaluation And Emission Analysis of Variable Compression Ratio Direct Injection Diesel Engine. 2.

Needelman, W.M., Madhavan, P.V., 1988. Review of lubricant contamination and diesel engine wear. *SAE Technical Paper.*

Nilsson, J., Bertling, L.J.I.T.o.e.c., 2007. Maintenance management of wind power systems using condition monitoring systems—life cycle cost analysis for two case studies. 22, 223-229.

Rodrigues, A.D.L.P., Santos, M.S., Serra, M.C., Pinheiro, E.M.J.I.J.o.I.E., 2017. A utilização do ciclo PDCA para melhoria da qualidade na manutenção de shuts. 9, 48-70.

Singh, R., Gohil, A.M., Shah, D.B., Desai, S.J.P.E., 2013. Total productive maintenance (TPM) implementation in a machine shop: A case study. 51, 592-599.

Stenström, C., Norrbin, P., Parida, A., Kumar, U.J.S., Engineering, I., 2016. Preventive and corrective maintenance–cost comparison and cost–benefit analysis. 12, 603-617.

Cazetta, Aline Mariane. Os interesses e os atores sociais em jogo nos artigos científicos sobre o agronegócio. 2018. 52 f. TCC (Graduação) - *Curso de Ciências Sociais, Instituto de Ciências Sociais, Universidade Federal de Uberlândia, Uberlândia,* 2018.

Costa, D. A.; Andrade, R. B.; Caetano, O. H., 2015. Manutenção linear em frota de colhedora de cana. *Sciencomm*, Uberlândia, p.65-79, 01 maio 2015.

Monteiro, C. I.; Souza, L. R.; Rossi, P. H. L., 2010 Manutenção e Lubrificação de equipamentos. Baúru, p.2. Oliveira Diogo Vargas de. *Relatório de atividades*

Pereira, Mário Jorge. Engenharia de Manutenção: teoria e prática. *Editora Ciência Moderna.* 2009. SENAI.

Ribeiro, Jéssica Borges; GOMES, Mayara Cardoso. Manutenção preditiva em motores de combustão interna por análise do óleo lubrificante. 2016. 76 f. Monografia - *Curso de Curso Superior de Tecnologia em Manutenção Industrial, Instituto Federal de Educação, Ciência e Tecnologia Fluminense*, Campos dos Goytacazes, 2016. Disponível em: <http://bd.centro.iff.edu.br/handle/123456789/1189>. Acesso em: 01 maio 2016.

SILVA, Rafael Nascimento., 2018 Manutenção preditiva por meio de análise de fluidos aplicada em Tratores agrícolas. 48 f. Dissertação (Mestrado) *Universidade Federal de Uberlândia.*

7. RESPONSIBILITY NOTICE