TPM Maintenance Management Model Focused on Reliability that Enables the Increase of the Availability of Heavy Equipment in the Construction Sector

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Abstract. The purpose of this paper is to present a maintenance study focused on total productive maintenance (TPM) and reliability-centered maintenance (RCM). Its approach is based on the first pillars of TPM, preventive and autonomous maintenance, as well as the FMEA analysis of RCM for maintenance analysis, which was conducted in this study. The implementation of TPM was successful in that various preventive maintenance (PM) policies assigned to the assets were implemented and it was demonstrated that TPM application in the construction industry could reduce the excessive accumulation of maintenance with the same effective optimization, and with support from RCM analysis and its heavy equipment systems analysis. Excessive corrective maintenance accounts for high investment and delay rates in work times of the assigned project. Traditional methods of availability guarantee, such as reactive or routine maintenance, are insufficient to satisfy a heavy equipment maintenance plan; therefore, what is called for is the systematic application of RCM and TMP because they allow the selection and application of effective PM tasks. An approach that develops and thoroughly analyzes the strategies of continuous corrective and PM is used with an atmosphere of uncertainty and with operational data limited by criticism. Results show a 90% improvement in availability.

1. Introduction
The role that an effective maintenance framework plays in organizations has become more important in maintaining competitiveness in the global market. Zegarra [1] details that construction companies at an international level are immersed in World Class Maintenance, which refers to having policies and good working practices in administrative fields, as well as in the technical field. Today, the construction sector represents an important section of the country's economy, and its growth is driven by the great dynamism shown by public investment. According to INEI, companies in the construction sector grew in this fourth quarter by 79.6% when compared with 2016 growth numbers in the same
quarter. The projects assigned for 2019 involve infrastructure improvement and the expansion of a category that the Peruvian Chamber of Construction reckons would reach 4.5% growth when compared with the previous year’s growth numbers.

The studies conducted indicate that the adoption of a good maintenance strategy allows us to keep the machines operational. However, the increase in mechanical forms and the complexity of the systems lead to an increase in unplanned failure shutdowns. Qarahasanlou, Barabadi, and Ayele [2] point to component failure as resulting in downtime; the lack of system availability; and consequently, substantial losses in production performance, high maintenance costs, and so on. Jain & Shingh [3] indicate (1) that small- and medium-sized enterprises must adopt, through their department or maintenance area, focused improvements, both preventive and autonomous, that are part of the TPM model, (2) and that the implementation of the indicated methodology increases availability, performance, quality, and efficiency. On the other hand, En-Nhaili and Bouami [4] use the system dynamics approach to model and analyze a maintenance system in order to evaluate the reliability of the equipment. Shmatkov and Shmatkova [5] indicate that the operating cost per hour can be reduced by an increase in equipment operating efficiency (EOE) in much the same way that Davies [6] pointed out years ago regarding the EOE, which is a measure of the efficiency and performance of the equipment that is directly linked to TPM. This measure focuses mainly on production losses where maintenance policy is one effect among many others. In the development within the semiconductor industry, Shin & Ahmad [7] tell us that the key to the success of TPM is the development of the practice of autonomous maintenance (AM), which refers to human capital among operators supported by technicians and engineers to perform simple daily maintenance activities, apart from the planned maintenance. Conversely, Carlson [8] tells us that the RCM approach allows us to improve this availability and thus to maximize performance through FMEA (Failure Mode and Effects Analysis) for the evaluation of the development of preventive maintenance (PM). The result is an improvement in the availability of equipment and a reduction of the maintenance cost.

2. State of the art

2.1. Maintenance Management Model

Riquero [9] asserts that the quick changes in business demand in the current economic environment has led organizations toward higher efficacy and efficiency in all aspects, and Edwards and Love [10], on the basis of their research, have determined that fixed-time (scheduled) and daily maintenance of infrastructure and machinery for construction projects is a basic requirement for productive and safe operations at the site. Among their results, courses for operators skills, onsite management training, and higher regularization stand out. Consequently, a model composed of protocols and maintenance procedures—that may be implemented throughout the organization—has to be designed.

2.2. TPM – (Total Productive Maintenance)

C-C Shen [11] explores in detail the performance of TPM development in companies, by means of planning, execution, and methodology objectives with the work team, operators, and management; this will enable the improvement of equipment and operations through failure reduction. The result is the 12-step TPM implementation and a process that may take 3–5 years to implement. While Amad, Abdul, Kamaruddin, and Min [12] agree that the key to TPM’s success is developing the autonomous maintenance (MA) practice and increasing the availability and reliability of machinery; this is connected with the development of human capital among operators supported by technicians and engineers to conduct daily maintenance activities, which are easy but the key is to follow up the process on top of the planned maintenance.

2.3. RCM – Reliability-Centered Maintenance:

The maintenance response when it comes to error prevention is to set a maintenance program. Prabhakar [13] shows a maintenance model based on preventive maintenance (PM) and predictive
maintenance (PdM) that gets integrated with the initial processes of reliability-centered maintenance (RCM). Sillivant [14] underlines that the proposed analysis of studies of RCM aims mainly at improving the availability of machines so as to maximize production. However, as he clears up for the operation processes, there are difficulties in adopting the RCM standardized methodology, mainly because of the complexity and the great deal of analysis that it entails (a long time is required for study and analysis), which results in an extended implementation, involving the services of an optimal number of qualified people.

2.4. RCM AND TPM
As Fah and Ekpiwhe [15] put it, maintenance is defined as a set of actions taken to guarantee that the systems or components provide the planned functions with a key target, that of preserving or restoring reliability. Rimawan and Bambang [16] state that the integration of a maintenance system for total productivity is vital to the determination of the degree of collaboration for the general efficiency of heavy equipment. The operation progress of each machine should be thoroughly monitored to measure its efficacy and efficiency. However, Holt and Edwards [17] point out that a key element of operational productivity is the operator’s capacity, when faced with the need to act quickly, to keep the operability of heavy machines.

3. Contribution

3.1. Fundamentals
The existing model enables the monitoring of the need for the prevention of mistakes by means of a maintenance program based on condition and time-controlled tasks.

Unlike the initial model mentioned by author Deepak Prabhakar and Dr Jagaty Raj, who propose predictive maintenance, that is to say, “on time” maintenance practiced on equipment. Autonomous maintenance will be implemented as the equipment is of the heavy machinery type and as the functions/activities that they fulfill make it impossible to carry out any kind of maintenance during the process. Apart from that, authors Shin, Rosmaini Ahmad, Kamaruddin, and Abdul help us in integrating the autonomous methodology to adjust the activity timeframe to the four stages of MA so as to take preventive and ongoing improvement measures toward operation. After executing TPM, RCM is performed, where it is mentioned how the methodology helps to reduce the pre-fixing logistic time and to define the “how to,” in accordance with the terms defined in the TPM steps and in relation to the application of the optimal maintenance system for heavy equipment, either preventive or autonomous (major pillars used). The objective is to build and totally execute an organizational culture that is centered around Kaizen and on the zero defect or breakdown principle.

3.2. Proposed Model

3.2.1. Autonomous TPM. To develop the autonomous maintenance practice (AM) and increase the availability and reliability of machines by means of daily tasks performed by operators, including checkups, lubrications, cleaning, and interventions. The advantage is the improvement of equipment performance and personnel skills.

3.2.2. Preventive TPM. This involves preserving equipment or premises by performing reviews and repairs that may guarantee working and reliability. The advantage is the prevention of failure and the retention of equipment capacity.

3.2.3. RCM. This type of RCM is a methodology that is based on the analysis of failure in a productive system by directly attacking the root of the problem. The main objective is to increase availability and reduce maintenance costs.
3.3. Components of the Model Proposed

The devices made are the following records for the correct functioning and monitoring of the maintenance program:

![Figure 1. Maintenance model](image)

| No. | Training steps                                                  | 4/03/2019 | 5/03/2019 |
|-----|----------------------------------------------------------------|-----------|-----------|
|     |                                                                | 9:00 a.m. | 10:00 a.m.| 11:00 a.m.| 12:00 p.m.| 1:00 p.m.| 2:00 p.m.|
| 1   | Work team building and line maintenance activity description.  |           |           |           |           |           |           |
| 2   | Skid steer and backhoe machine selection and description.     |           |           |           |           |           |           |
| 3   | Machine technical specifications.                             |           |           |           |           |           |           |
| 4   | Specifications of each machine system, piece, and part.       |           |           |           |           |           |           |

![Figure 2. Maintenance training program](image)

The audit program for autonomous maintenance, which takes place in the first part of the model, is intended to execute an audit on workers about the correct functionalities (Figure 3).
AUTONOMOUS MAINTENANCE AUDIT PROGRAM SHEET

EQUIPMENT No.: MC1 AREA: Maintenance
RESPONSIBLE: Engineer Perez AUDITOR:
START DATE: 07/06 ENDING DATE: 08/16

| AUDIT ITEMS                                      | EVALUATION SCALE (BAD-GOOD) | UPGRADE RECOMMENDATION |
|-------------------------------------------------|-----------------------------|------------------------|
| 1 Team AM program goals understanding           | X                           | X                      |
| 2 Team AM program goals understanding           | X                           | X                      |
| 3 Management team AM activities planning        | X                           | X                      |
| 4 Operation team AM activities implementation   | X                           | X                      |
| 5 Cooperation between teams                     | X                           | X                      |
| 6 Communication between teams                   | X                           | X                      |
| Decision according to evaluated score           |                             |                        |
| >50 = good and looking for future upgrades      |                             |                        |
| 40–49 = minor upgrades                         |                             |                        |
| <39 = requires modification in AM practice      |                             |                        |
| TOTAL                                           | 25                          |                        |

Figure 3. Maintenance audit

This is interpreted as the steps that are required for training evaluation and that enable the project manager to measure the range of activities and the collaboration of MA teams.

A logbook of each machine records the type of maintenance and repairs made under the program proposed. This recording is conducted in the final part of our model in accordance with the improvement of the design that composes the RCM block (Figure 4).

This allows us to identify the most frequent failures and the tools necessary for its operating reliability, which are represented in the total life hours of each skid steer loader or backhoe machine.

3.4. Suggested Method
The investigation detail is adapted as a change in maintenance processes in which TPM and RCM coexist by representing the main axis for the development of maintenance activities and processes. (Figure 5)

3.5. Indicators
The indicators shown below are as follows

\[
TPEF = \frac{Total\ operating\ hours\ of\ equipment}{Total\ reported\ failures}
\]  \hspace{1cm} (1)

\[
TPPR = \frac{Corrective\ intervention\ total\ time}{Total\ corrective\ shutdowns}
\]  \hspace{1cm} (2)

\[
Availability = \frac{TPEF}{TPEF + TPPR}
\]  \hspace{1cm} (3)

5
4. Validation

4.1. Case Study
The company under review is MACISAC PERU SAC. Its capital is 100% Peruvian, and it has had a presence in the national market for 9 years. The company rents machinery and accessories for the development and implementation of specialized engineering projects during external domestic gas pipe installation, sanitation, construction, and agroindustry. Nowadays, MACISAC has a line of eight skid steer loaders and one backhoe, which bear the CASE trademark, and which are being used in the water supply networks project for the client Grupo Cobra (1 year and 8 months up to date), which is located in San Bartolo district, Lima province, Peru.

4.2. Diagnosis
The following graphic shows the effective capacity of each piece of heavy machinery in the current situation of the company under study.

A simulation using the Arena Simulation Software package was carried out, with time and activity data gathered to perform a maintenance program for heavy machinery (Figure 7) during the analysis of skid steer loaders.

- Average current maintenance hours: 13.18 hours
- Maximum current maintenance hours: 57.68 hours
- Average time between failures – Current: TPEF: 24.62
- Average time for failure repair – Current: TPPR: 15.24
- Availability rate – Current: 85%
Figure 5. Process mapping (proposed)

Figure 6. SR220 Case skid steer

Figure 7. Effective vs. Expected capacity

4.3. Apply Model in C.E.
To reduce shutdown hours and improve machinery availability, an improvement proposal in the maintenance program of the company was conducted. Using these methodologies, the activities for
each skid steer loader are to be standardized to the real hours that they must operate. Thus, processes will be more efficient. The proposed flow chart for a maintenance program has the following steps:

4.3.1. Machines arrival. This is the first step of the maintenance program, where a machine (e.g. a skid steer loader) has had a failure that will be evaluated, and the necessary activities carried out for it to continue working. In this phase, the machine may be revised in the garage or field.

4.3.2. Machines receipt. In this phase, a responsible operator will receive the machine and make a decision about earmarking it for preventive or corrective maintenance.

4.3.3. Machine status analysis. It is based on machine failure analysis, which has been previously recorded, with the purpose of avoiding them in the future with PM. This is because they may have serious consequences and their criticality level is high.

- **Repair:** The diagnostic tests detect a minor failure type, the likes of which can be repaired at once without detailed planning; hence, repairs may be carried out in the field.
- **Planning:** Maintenance type to be carried out has been planned. Preventive/Corrective.

4.3.4. Work order issuance. This activity is carried out before allocating resources, so as to monitor it in a better way and to manage the inventory of required parts for the maintenance task. Thus, the following operation times are reduced as pauses are shorter.

4.3.5. Available resources monitoring. If the required inventory is not available, materials, tools, and/or spare parts will be ordered.

4.3.6. Maintenance operation type assignment that will be performed on the machine. Regarding the current model of the company, this proposal includes autonomous maintenance at this stage as it is carried out to root out the causes of failure found in the heavy machine. At the same time, it is measured and monitored according to the stipulated parameters. A team trained for each required task carries it out and considers all the steps that have been taken and appear in the records. This team receives constant feedback, as well as audits.

4.3.7. Machine logbook preparation. The results and observations were recorded in writing. All the details of the maintenance activities performed for each machine are registered there, and this is part of a database for the modal analysis of failures and effects.

4.3.8. Exit of machine in good condition. The heavy machine returns to its task in the field, and the project continues to be in process without delays.

4.4. Results
On the basis of the results obtained from our proposed model, heavy machine availability greater than 85% in the company MACISAC PERU SAC was revealed. This means that on a monthly basis, shutdowns will no longer occur throughout the construction project. Similarly, the time for the proposed maintenance model was measured.

The availability increases to 81% (Table 1) compared to 62% obtained firstly, shows that our proposed model has innovative ideas gathered from different authors who have also dealt with the same problems in the sector under study. Apart from these integrated models, the best methodologies for organization performance in the water pipes installation project in San Bartolo were integrated. This allows for better control over the maintenance activities performed and helps to determine the critical components to mainly supply these resources.
With the help of the simulation model, the results showed an improvement in the saving of hours because of heavy machine maintenance. This was taken to cost per hour of work, which allowed us to see the savings in overtime and downtime per skid steer loader as shown in Table 2.

| Table 1. Indicator         |
|---------------------------|
| **INDICATOR** | **PROPOSED** |
| AVERAGE MAINT. HOURS | 7.50 |
| MAXIMUM MAINT. HOURS  | 17.80 |
| TPEF               | 30.08 |
| TPPR               | 7.24 |
| AVAILABILITY RATE   | 81%  |

| Table 2. Saving in overtime and downtime |
|------------------------------------------|
| **REASON** | **AMOUNT** | **%** |
| Savings in overtime savings in downtime | S/44,800 | 14 % |
| TOTAL      | S/311,235 | 100 % |

Costs were allocated for each type of methodology on the basis of research on case study-related articles, manpower, consultants, and specialized personnel who will be in charge of the measurement of activities. In addition, an investment of S/18,275.00 was estimated, which contains all the necessary resources, such as records, electronic devices for real-time control, and equipment and tools for those involved in the process shown in Table 3.

| Table 3. Cost of methodologies |
|--------------------------------|
| **5’s** | **TPM** | **RCM** |
| MO      | S/1,800.00 | S/1,425.00 | S/1,300.00 |
| Consultants | S/4,000.00 | S/4,000.00 | S/1,250.00 |
| Specialized personnel | S/2,000.00 | S/2,000.00 | S/2,000.00 |
| **TOTAL** | S/7,800.00 | S/7,425.00 | S/4,550.00 |

| Table 4. Investment |
|---------------------|
| **TOOL** | **RESULT** |
| VAN     | S/10,310.31 |
| TIR     | 3.56 % |
| COK     | 1.13 % |
| COST-BENEFIT | 2.41 |

The following data were considered for the validation of the economic flow.

- Annual effective rate: 20%.
- Monthly effective rate: 1.53%
- Loan: S/10,965.00
- Fee: S/1,007.21 (French Method)
- Weighted average annual cost of capital: 13.56%.

Over a period of 12 months, investment was recovered for the implementation of the methodologies and the following results were obtained (Table 4).

This means that the proposed model will be profitable for the company for the first 12 months and increasingly long-term and user-friendly for the various construction projects in which the company is going to be involved.

5. Conclusions

- With the proposal of improvement, a 5% increase is possible in the general availability of the fleet of heavy machines and skid steers, which would allow the company under study to be at competitive levels within the national machinery rental market in the construction sector.
- By simulating the proposed maintenance process, the average waiting time between failures can be reduced from 13 hours to 7 hours. This means a 15% reduction in downtime.
- The proposal was feasible; the cost-benefit ratio was greater than 1, which will generate profits and savings.
To determine the root cause, different sampling methods were conducted in which the operators recorded the activities/incidences of the equipment. This was decisive for the hypothesis and the proposal of improvement.

The relationship between TPM methodologies and RCM allows a ramp-up of expert operator performance and interaction with machines with the objective of reaching zero defects.

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