Equipment Reliability Process with Predictive Maintenance (PdM) Technology: Advanced TPS based upon Highly Reliable Lean Maintenance at Toyota Manufacturing USA

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Abstract: - Equipment reliability plays a critical role in global production because the equipment specifications of production lines in the world vary depending on the circumstances of each country. When Toyota Motor Corporation operates overseas plants, equipment reliability management is one of the most important hurdles the global production must overcome. It is important to develop an equipment reliability management program to minimize support from Japan to let overseas plants become self-reliant. Therefore, the authors have proposed the Advanced TPS to achieve simultaneous, worldwide high-quality assurance in global production. Advanced TPS is comprised of four different pillars: productivity, cost, workability, and quality. This article explains how the Advanced TPS can be applied specifically to the equipment reliability process with Predictive Maintenance (PdM) Technology. This business practice focuses on managing equipment reliability to meet the business goals of Toyota Manufacturing USA.

Key-Words: - Equipment Reliability, global production, Toyota Motor Corporation, Advanced TPS, Predictive Maintenance (PdM), Toyota Manufacturing USA.

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1 Overseas Plant Challenge

Toyota Motor Corporation (Toyota) set the standard in manufacturing industries for producing products most quickly and efficiently because of the Toyota Production System (TPS), [1]. Normally, Toyota starts up a new model in Japan and works to improve the productivity of the production line and the reliability of the equipment through the production preparation period. Specifically, to guarantee the reliability of the equipment system, in addition to reviewing (redoing) the design defects of newly introduced equipment, it was common to move the equipment overseas plant and start production with stable reliability after eliminating initial defects.

However, the timing of demand in various countries around the world and the styles and specifications preferred by each country have become different, so it is necessary to provide different specifications for production facilities in each country, to lay out new production lines, and to start up new models smoothly to ensure the same global quality demanded by Toyota's customers. When comparing equipment performance and maintenance costs to Japanese plants, it was recognized that there was a huge opportunity to improve at equipment management process and control, [2], [3], [4].

When production is started on a new production line, Preventive Maintenance (PM) is generally carried out to maintain the reliability of the equipment. However, to replace parts at the recommendation of the equipment manufacturer, excessive replacement is required at a short frequency and considering the safety factor. This is not only because of the labor involved in maintenance, but also because the production line is often shut down for a long time due to having more spare parts than necessary to order from overseas, or because equipment parts are out of stock. Therefore, at present, the optimum replacement cycle of parts is required following the operating conditions and environment of the business entities engaged in overseas production, that is, conditions such as temperature and humidity. This paper reviews the process of ensuring lean facility reliability by utilizing facility sign management Predictive Maintenance (PdM) at Toyota Manufacturing USA, which is a major source of overseas production.

The Toyota Manufacturing USA mentioned here refers to Toyota Motor Manufacturing, Texas. This is the only plant that produces pickup trucks that are not produced in Japan. Therefore, it is not possible to use TPS, which is the traditional concept of Toyota's production line, as it is in Japan, and it is to formulate the concept of a new production line and aim for the same quality in the world by aiming at 100% automation rate. However, to achieve an automation rate of 100%, it is necessary to understand and configure the reliability of facilities and equipment. It is very important to develop an equipment reliability management program to minimize support that comes from Japan to let each of the overseas locations become self-reliant. Luckily, the business model of TPS can be utilized to greatly improve equipment reliability management.

2 Advanced TPS for Maintenance Management

The TPS is frequently modeled as a house with two pillars as shown in Figure 1. One pillar represents Just-in-Time, and the other the concept of Jidoka. Jidoka is "Building in Quality" at the process and Just-in-Time is building what is needed, when is needed in the amount needed. Toyota has always had the philosophy of stopping the line when defects are found; this can be done by anyone who sees a discrepancy with a known standard (what should be happening within a process). In the proposed Advanced TPS as shown in Figure 2, global production aims to achieve the same quality and optimal location worldwide. This paper focuses on (b) a Highly reliable production system among the four components. Toyota has set a goal of 95% operation rate, which is the same worldwide. To achieve this goal, not only the training of workers but also the reliability of the base equipment is the key. It is essential to develop facilities that prevent the line from stopping due to equipment failure by identifying the weakest parts of the components of the production line, predicting the failure of the components, and maintaining them immediately before the failure occurs. This paper describes in detail how the Texas Plant, which produces the largest vehicles in Toyota Manufacturing USA, has constructed a highly reliable production system with lean facilities that can predict and replace failures of component equipment efficiently because the equipment has a high automation rate of 100% and is based on full automation.

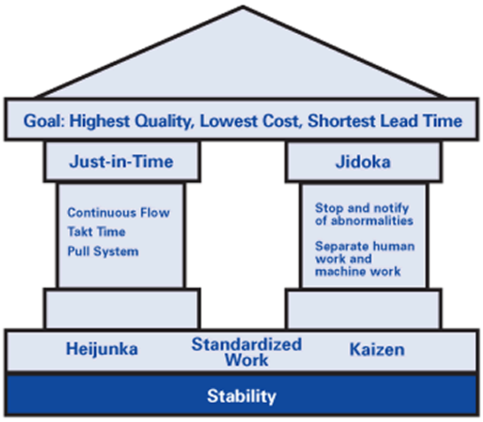

Fig. 1: Toyota Production System House

Originally, the authors have focused on utilizing these concepts in the manufacturing quality control process. After these were studied deeper into these concepts, it was found that they fit very well with the equipment reliability management process. Therefore, the authors have proposed the Advanced TPS to attain high-quality assurance in global production, [5]. Advanced TPS is comprised of four different pillars: productivity, cost, workability, and quality. This proposal focuses on the pillar of productivity by raising the standard of maintenance management to match manufacturing to achieve optimal performance of equipment that directly contributes to achieving company goals.

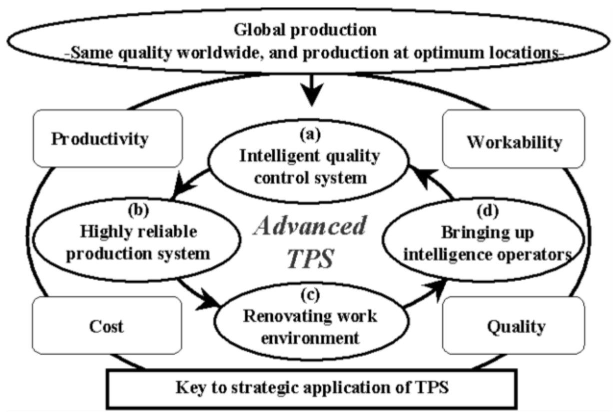

Fig. 2: Advanced TPS model

2.1 Just-in-Time

The authors can utilize this equipment health condition pattern to examine how maintenance work is set up as shown in Figure 3. The right work is the minimum amount of work necessary to ensure the equipment provides the necessary level of performance.

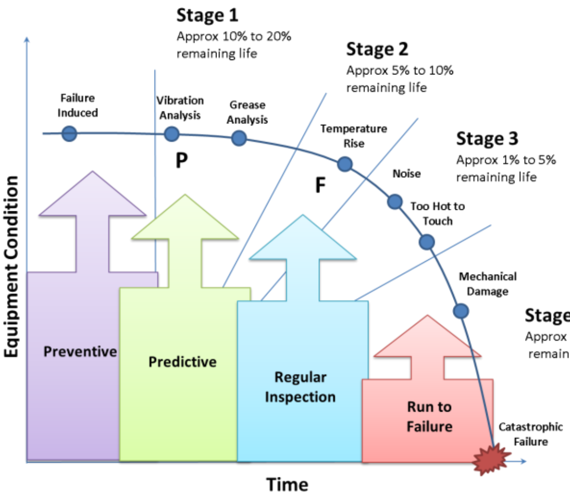

Fig. 3: Equipment Health Condition based on Different Type Maintenance Work

Since there are many operational factors contributing to equipment failures, even the equipment manufacturer cannot provide a very accurate maintenance frequency. Plants need to identify the correct maintenance frequency based on Condition Based Maintenance (CBM). Other techniques such as equipment health monitoring are installed to allow us to intervene before loss of equipment function [6]. The authors also utilize communication within plants to identify new failure patterns. Work identification is the cornerstone of reliability improvement and represents a fundamental shift from conventional Time-Based Maintenance (TBM) to an equipment reliability approach to maintenance. The Point of Failure (PF) curve in Figure 4 shows how equipment deteriorates over time or cycles, and where team members can provide an additional line of detection should failure initiate between Predictive Maintenance (PdM) collection dates. In most cases when a team member can identify the function issue at Stage 3 in Figure 3, the time loss is inevitable. It is very important to identify the deviation of equipment health condition at Stage 1. One important note is the time span of each stage can vary on the same equipment due to operational conditions that change and other variables. An appropriate change management implementation approach must be used. The method is to follow up and define special maintenance frequency after each change point.

However, sometimes an unknown change point is introduced into equipment. The quality of each maintenance work performed can vary. That will change the equipment's working condition.

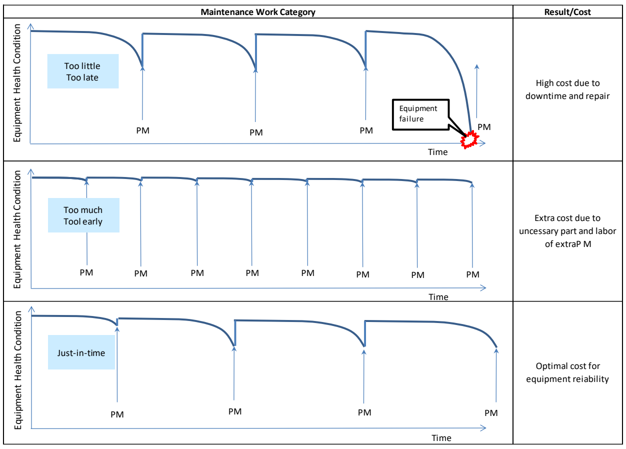

Fig. 4: Time-Based PM vs Just-in-Time PM

The working condition of equipment can also change as well from other intentional reasons (e.g., production speed increase, payload increase) or unintentional reasons (e.g., Humidity change, dust). These factors have a direct impact on the equipment's health condition. As shown in Figure 5, equipment's healthy operation time varies based on operation conditions. It is critical to detect this operation condition change to prevent equipment damage. To achieve this goal, the authors need to introduce another pillar of TPS, Jidoka, into the equipment management process to ensure equipment reliability is maintained.

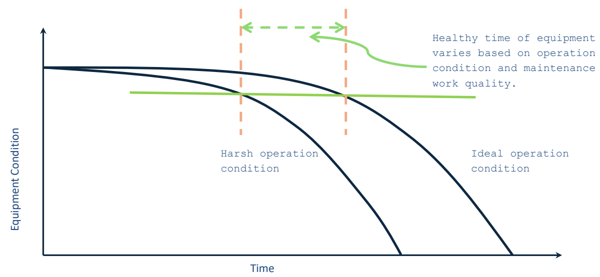

Fig. 5: Equipment Point of Failure (PF) Curve vs Equipment Operation Condition

2.2 Jidoka

Jidoka plays an important role in the equipment reliability process throughout the whole life of equipment as shown in Figure 6. The first step of Jidoka in equipment reliability is a process that simply delivers the inherent capability of the equipment "by design" to meet the equipment performance requirements. From design, and build to buy-off, the plant needs to get involved to make sure the equipment meets all specifications. Any "quality" gap needs to be corrected immediately before or during installation. However, at this stage, the line is designed based on the replacement time recommended by the equipment manufacturer, which may result in excessive-quality equipment. Toyota, therefore, uses the experience of its production engineers to analyze the failure history of similar production lines to design slimmer and cheaper lines. It should be noted here that the production line recommended by Toyota is based on Jidoka's idea that things flow centrally, and once a facility stops due to a malfunction, the entire line stops. On the other hand, the production line of the same industry is configured not to stop the line by providing a buffer line or buffer, and the line configuration becomes complicated and more expensive, [7], [8].

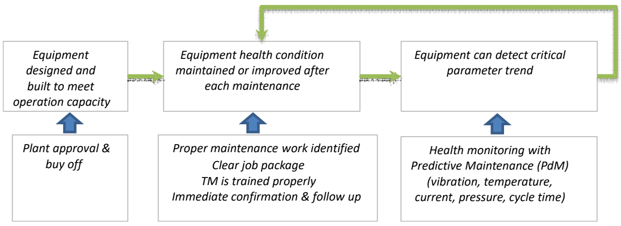

Fig. 6: Maintenance Jidoka through Equipment Life

Another feature is the use of detachable sensor devices. When the weakest part of the production line is identified, and analyzed, and countermeasures are taken, the weakest part is transferred one after another. Each time, it is necessary to identify, analyze, and take measures against the site concerned. It is the basic requirement of this paper that symptom management can be flexibly carried out like this. Figure 7 shows a vibration sensor mounted on a large motor in order to monitor the motor operation condition.

Figure 8 shows the vibration data collected by the sensor as shown in Figure 7. The amplitude of the vibration data increased over the time which indicated the motor vibration increased because one or more components of the motor deteriorated. Zone 1 data indicates the motor operates in healthy condition. Zone 2 indicates the motor starts to lose healthy operating condition. In this specific case, the bearing of the motor was not lubricated adequately so excessive wear was generated between the bearing ball and races. The wear of the races generated vibration when the motor was running, which is shown in Zone 3. Although the motor still ran to maintain the production, the wear of the race got worse without maintenance or repair. When the race wear reaches to certain level, the motor will fail and shut down the production. The white zone in the data collection is a healthy working condition. The yellow zone indicates the motor is losing optimal operation condition and has started to wear. The red zone indicates the motor races start to wear and most time, it leads to irreversible condition. If the motor is repaired early enough, then just need to replace the bearing which is a small portion of the cost of the motor. If the motor is not repaired soon enough, which is shown in Zone 4, a new motor is needed to replace the damaged one which introduces a high production cost. From this example, it is clear that if the maintenance work is conducted at Zone 2, there will be no damage to the motor. Thus, there is no need to conduct the repair work.


Fig. 7: Vibration Sensors for PdM system

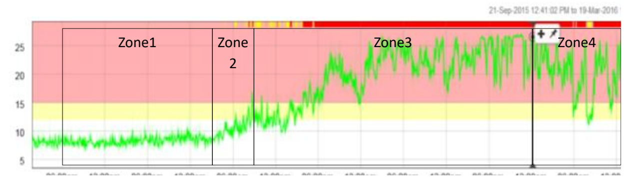

Fig. 8: Vibration data of a motor from healthy to abnormal operation

3 Problem Solution

Introducing the PdM into equipment management requires the development of the equipment reliability process and a formal business process to sustain it. The authors utilized the PdM method with a focus on equipment directly linked to the Computerized Maintenance Management System (CMMS) to enhance the work identification process. With this right process in place, the authors can ensure that the maintenance system is doing the right things at the right time to maintain equipment in ideal condition.

With the objective to lower costs and improve return on assets, the lean maintenance equipment care philosophy is about "autonomous maintenance". While this concept of lean maintenance is a valuable starting point for optimizing equipment performance at optimal cost, it falls short in the technical validity of the equipment reliability program. The utilizing PdM way to make the transition from reactive to proactive is to enhance the work identification process. Rather than relying on our current program of reactive work requests and mostly time-based PM.

The lean maintenance process starts with the identification of equipment performance requirements based on business goals as shown in step 1 in Figure 9 (Appendix). Next, it determines the equipment that is most critical when they fail, and where the risk is highest in terms of impact on business performance. For this equipment, the authors establish specific performance targets. This stage focuses maintenance reliability improvements on the performance targets of critical equipment that contribute most to the company's success as shown in step 2.

The failure identification stages identify and prioritize gaps in performance by conducting specific component-level performance analyses. The failure mode and impact on business is identified for each component, as shown in steps 3 to 4. Then all contributing factors to equipment abnormalities are identified as shown in step 5. At this stage, the production line equipment of the main process is subjected to an endurance test to eliminate the initial failure of the equipment. Concretely, the equipment is repeatedly operated throughout the night by performing the sequence so that the line moves continuously without producing parts. By doing so, it is possible to construct a stable facility by detecting faults lurking in the facility in advance, although abnormalities related to components cannot be eliminated. Before any improvement, the authors study the original maintenance PM work to identify the gap between scheduled work and all potential failure causes. If work is not set up to point to any failure mode, they are identified as waste as shown in steps 6 and 7. The study includes an assessment to determine gaps between the current and future state and identifies specific opportunities for improvement. The countermeasure or improvement plan is also included with cost and justification.

One of the toughest challenges on the road to improved equipment reliability is to determine the prescription of proactive work that should be done to maintain the equipment so that they deliver the reliability what is needed at optimal cost. This task is known as "work identification", and it is the essential element of an effective equipment reliability process.

In stages 8 and 9, the appropriate work identification strategy is followed to understand and address all causes of failure for the equipment under consideration.

In the past, the work identification of stages 8 and 9 is based on team members' feedback of equipment status during their scheduled maintenance work. There are two shortcomings of this method. First, this feedback quality is based on team member skill and experience level. Inexperienced team members can not identify the equipment operating condition change which will lead to equipment damage. The second issue is the feedback is based on scheduled work. It might be too late for team members to feedback on the issue before irreversible damage to equipment occurs.

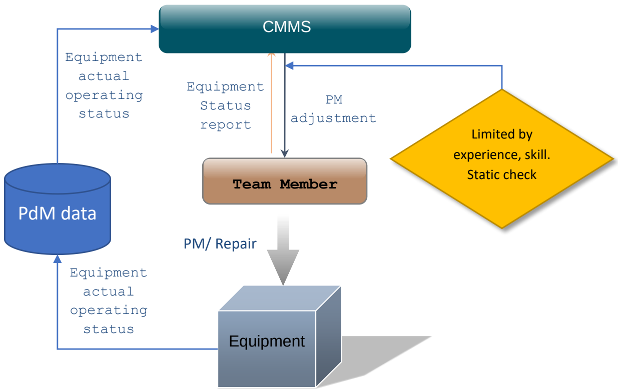

Fig. 10: Vibration data of a motor from healthy to abnormal operation

In the new lean maintenance system, PdM data is directly linked to CMMS [9], as shown in the left channel in Figure 10. It closes the gap in the traditional work identification process. The resulting equipment reliability program includes a mix of PM, detective maintenance, PdM, and some run-to-failure decisions based on their business impact.

The core of this lean maintenance practice is identifying the operating condition change through equipment PdM data analysis, which leads to certain corresponding maintenance work. The outcome of the work identification element is the right work at the right time (the right work is defined in terms of the tasks and the timing for conducting them). The process is self-sustaining, with opportunities to continuously improve and evaluate the overall effectiveness of the equipment reliability process as well as revisit reliability programs and continuously improve, as shown in step 10 of Figure 9 (Appendix).

As a case study, the most effective application of symptom management was found in the temperature control system of the drying furnace for painting. Once the temperature controller fails, it takes a long time to replace it. In addition, there was no sign of failure because it was installed in a place where workers usually do not enter. This time, we were able to predict the failure in advance and replace the equipment parts, which contributed to a significant improvement in productivity.

In the future, it is expected that the application of the decking process (the process of combining the driver's seat and the frame) specific to the pickup truck production line in which the sensor is set will contribute to the improvement of equipment reliability in the pickup truck production line.

4 Case Study

This section describes in detail what was done in the Paint department of Toyota Motor Manufacturing Texas, USA. Figure 11 shows an overview of the PdM system installed in the Paint Department. For 874 PdM observation points, 1,485 sensors are installed, and sensor data is integrated and managed in the server database via Andon PLC (Programmable Logic Controller) and Cloud, and diagnosed by SMART Diagnostics, [10].

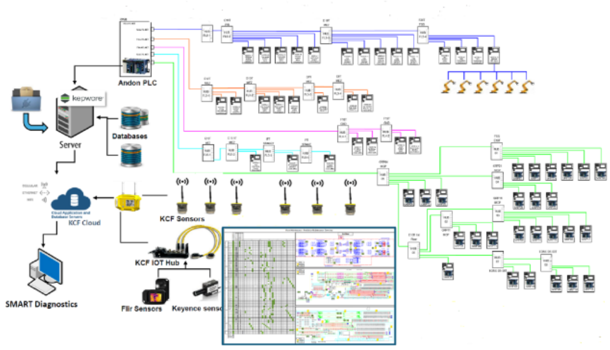

Fig. 11: Paint shop PdM system overview

Next, an example of preventing a long-time stop of a production line from the diagnosis result is introduced. The first is on the bearing of the fan motor of the coating drying furnace. As a result of trend management of the vibration velocity data from the sensor installed in the fan motor, the vibration width gradually increased as shown in Figure 12. Furthermore, when the frequency analysis was conducted on the data, it was found that the part where the amplitude width increased had periodicity, and it was estimated that some kind of mechanical failure (backlash occurred and vibration started) had occurred in the bearing. Then, when the bearing was replaced, the flaking phenomenon started, and if it continued to be used, it would cause burning and a long time to stop the production line.

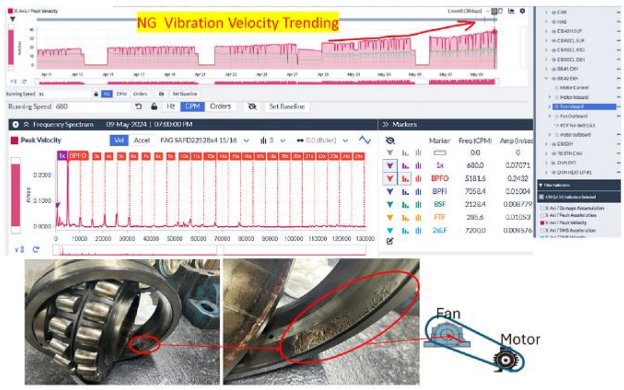

Fig. 12: Downtime prevention example with PdM

The second is about the chain conveyor which tows the object in the air transport system. This is an example of monitoring the degree of wear of the chain. The graph in the center of Figure 13 shows the degree of wear of the chain in the time series. It shows that the wear of the chain is progressing. When the chain was replaced due to approaching the control limit, it was able to be replaced just before the chain was broken.

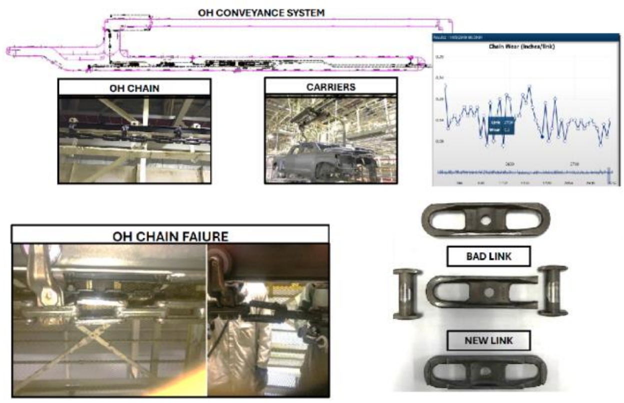

Fig. 13: Downtime prevention example with PdM

Figure 14 shows the effect of PdM in improving the reliability of the equipment. This shows the amount of investment for PdM, the long shutdown time of the facility to shut down the production line, and the converted amount. A total of 335 hours of equipment downtime was prevented up to 2024, which is equivalent to $16.38 million. The PdM investment cost was approximately $700,000, and it was enable to enjoy significant cost benefits.

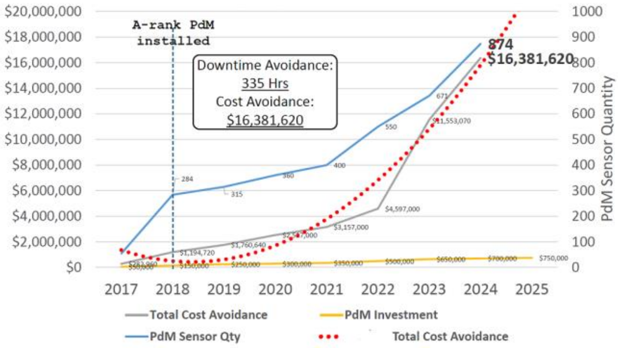

Fig. 14: Equipment reliability improvement with PdM

Furthermore, by deriving the optimum life of the equipment, constituting the production line as a side effect, it was possible to greatly contribute to the improvement of the reliability of the whole equipment of the production system, [11]. At present, by deriving the optimum life as shown on the right for about 89% of the components as shown in Figure 15, 1,488 components have been able to construct a production line with high equipment reliability at a minimum cost by replacing the components at a cycle unique to the line.

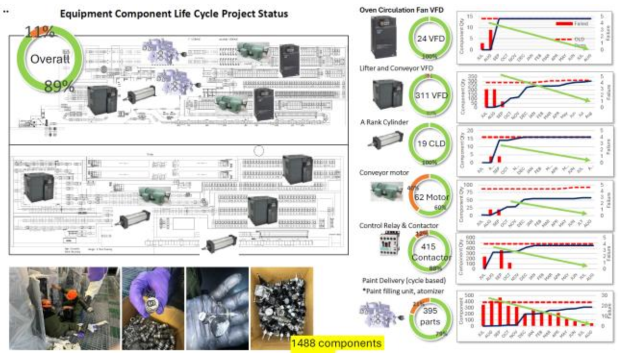

Fig. 15: Equipment component life cycle project status

5 Conclusion

The authors have confirmed the lean maintenance system with PdM is effective and proactive to improve equipment reliability, thus, improving business performance over time. This method is feasible and has a low cost. Lean maintenance can achieve optimal equipment reliability, which means that for the least possible cost, the authors achieve the level of performance twhat is needed from our equipment in order to meet our business goals (plant or company level goals).

The process is self-sustaining, with opportunities to continuously improve and evaluate the overall effectiveness of the equipment reliability process as well as revisit reliability programs and continuously improve. These activities optimize the effectiveness of the TPS and Advanced TPS.

This study contributes to the equipment reliability management issue and the productivity improvement strategy by proposing how to engage employees to improve equipment performance. This study is also expected to contribute to the extension of the Advanced TPS concept in a real manufacturing environment.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Pengjiu Li has implemented Figure 7 and 8, in other words, they were developed at the paint department in Toyota Motor Manufacturing, Texas. In addition, Joe Li discussed chapters 1-3. The description of Figure 2 was improved by Hirohisa Sakai.
- Hirohisa Sakai has proposed the Advanced TPS and adopted into Toyota Manufacturing USA, especially for highly reliable lean maintenance. In addition, Hirohisa Sakai, in particular, collected and elaborated on examples from the field in Chapter 4.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

There is no particular source of funding. This is a personal paper on symptom management that was empirically studied at Toyota Texas.

Conflict of Interest

There is no problem with conflicts of interest.

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APPENDIX

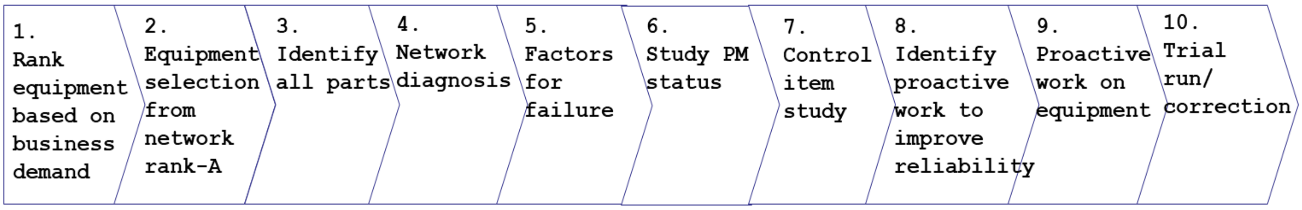

Fig. 9: TPM Process Flow