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Implementation of Autonomous Maintenance and its Effect on MTBF, MTTR, and Reliability of a Critical Machine in a Beer Processing Plant

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Abstract — This research is part of plant reliability improvement program of a beverage manufacturing company that specializes in beer production and packaging. Two months of machine breakdown data gathered showed that the glass bottle filler/crowner had the longest downtime of 96.62 hours and was fast becoming a critical machine. With the plant fully automated, availability of the critical machine became a key issue because breakdowns were more likely to affect production and product quality. To reduce maintenance pressure, autonomous maintenance (AM) was introduced on the bottle filler/crowner as part of total productive maintenance. The aim of the AM program was to optimize machine availability through education and upskilling of shop floor operators to a level where they can take care of minor maintenance jobs on their equipment so that skilled maintenance people can concentrate on value-added tasks and technical repairs. Before implementing AM, the bottle filler/crowner had an average MTBF of 87.42 hours, average MTTR of 1.15 hours, a shift (12 hours) reliability of 87 %, and a complete day (24 hours) reliability of 76 %. After implementing AM for two months, there was a noticeable increase in MTBF to 113.27 hours, a decrease in MTTR to 0.87 hours, and an increase in machine reliability to 90 % and 81 % respectively for 12 and 24 hours operation. The results show that empowering operators in performing autonomous maintenance on their machines is key to detecting equipment failure, reduce breakdown, increase reliability, and improve machine performances.

Keywords — Autonomous Maintenance, Critical Machine, MTBF, MTTR, Total Productive Maintenance.

I. INTRODUCTION

Maintenance becomes a problem with the increased use of automation and mechanized systems such as just-in-time (JIT) and robotic systems in modern industries [1]. With automation, millions of things can go wrong in the millions of machine components at any one time. Equipment availability, therefore, becomes a key issue because a possible breakdown is more likely to affect production and product quality, with fewer maintenance technicians to carry out immediately required tasks [2]. To help reduce maintenance pressure, and increase machine availability, autonomous maintenance (AM) is introduced as part of total productive maintenance (TPM). The purpose of AM is to educate and upskill shop floor operators to a level where they can take care of minor maintenance jobs on their equipment so that skilled maintenance people can concentrate on value-added activities and technical repairs [3].

The AM program is a seven-step process [4]. These steps, according to [3], are: (1) perform an initial cleaning and inspection (2) eliminate sources of dirt and identify difficult to clean areas, (3) create cleaning, inspection, and lubrication standards, (4) perform a general, wide-scale equipment inspection, (5) carry out an autonomous equipment inspection, (6) organization and standardization of workplace, and (7) autonomous management for continuous improvement of policies, standards, and equipment. These steps are implemented to progressively increase operators' knowledge, participation, and responsibility for their equipment.

In step one of the autonomous maintenance program, the goal is to increase the basic understanding of machine components and train operators to perform a total cleanout (TCO). Although cleaning is generally perceived as a low-status, unqualified activity, it is considered a form of inspection in TPM. It plays an important role in identifying machine and component abnormalities along with sources of dirt, difficult to clean and inspect areas [4]. According to [5], inadequate cleaning can result in component failure, quality defects, and accelerated deterioration in equipment. Additionally, the dust and dirt buildup on equipment increase wear and frictional resistance, causing speed losses such as idling and underperformance.

Under steps two and three of the AM program, priority is placed on abolishing sources of dirt that cause accelerated deterioration, reversing deterioration, and establishing and maintaining basic equipment conditions [3]. The key to these steps is not to clean for the sake of cleaning, but to perform detailed inspections when cleaning. Here, the shop floor operators can discover the reasons for dirt, and identify reliable solutions for its removal. In doing so, the operators change from being reactive to working more proactively [6], achieving optimal conditions that eliminate stoppages as well as reducing component breakdowns and machine failures.

Steps four to seven of autonomous maintenance deal with general and autonomous inspection, reviewing and creation of standards, and enabling the operator to manage his equipment autonomously. Under these steps, the operators undergo training on machine pneumatics, electrical systems, hydraulics, lubrication system, drives, bolts, nuts, and safety standards [7]. With this knowledge, they are now well aware of their machines and can understand, manage, and improve their equipment and processes [8]. Additionally, the operators can also conduct visual inspections on major parts and find and fix minor defects based on created standards. The maintenance craftsmen can't detect and cover all the breakdown symptoms when machines are in operation [9]. By acquiring technical knowledge through AM, operators can help detect abnormalities in equipment and prevent symptoms from developing into catastrophic breakdowns.

II. Reliability, MTBF, And MTTR Of Critical Machines

In any production plant, machines can be divided into critical and non-critical. A critical machine is one with the longest downtime and has the most negative impact on the plant [10]. The reliability of a machine is the probability that the machine will perform or operate the required functions without failure under a given condition for an intended operating period [11]. Lower reliability means increased unplanned stoppages and consequently unscheduled repairs and decreased availability [12]. For any given equipment, reliability is measured by calculating its mean time between failures (MTBF) or mean time to failure (MTTF), and mean time to repair (MTTR) [13].

MTTF is used for non-repairable components, for instance, electric equipment like drive motor, while MTBF is used for repairable components, for instance, a rotating shaft or a pulley belt [14]. MTTR is the time it takes to run a repair after the occurrence of a failure. In other words, it is the time required for corrective maintenance [15]. MTBF and MTTR are two very important key performance indicators (KPIs) when it comes to the availability of a system, facility, equipment, or process [16]. The formulas for determining MTBF, MTTR, and reliability, R(t), are given in equations (1), (2), and (3), respectively:

$$MTBF = \frac{Operating\ Time}{Number\ of\ Failures} \tag{1}$$

$$MTTR = \frac{Downtime}{Number\ of\ Failures} \tag{2}$$

$$R(t) = e^{\left(-\frac{t}{MTBF}\right)} = e^{(-\lambda t)} \tag{3}$$

$$Where\ \ \lambda = \frac{1}{MTBF} = failure\ rate \tag{4}$$

The operating time of a production plant is the difference between available time and unplanned downtime [7]. It is the actual time during which the equipment is running, and dictates when an asset should be inspected, cleaned, adjusted, replaced, or reconditioned.

III. Research Methodology

A. Machine Downtime

Two months of historical machine breakdown data were gathered for the top three critical machines in a beer processing plant of a beverage manufacturing company. Based on this data, the bottle filler/crowner was identified as the plant's most critical machine having the longest downtime of 96.92 hours resulting from 92 breakdown events within that period. Table 1 and Figure 1 shows the downtime hours of the critical machines. Figure 2 is a picture of the most critical machine.

TABLE I. Machine Breakdown Data For Top Three Critical Machines

Machine	Breakdown Time (hr)	Breakdown Events
Bottle Filler/Crowner	96.92	92.00
Bottle Labeler	92.46	25.00
Bottle Washer	88.69	30.00

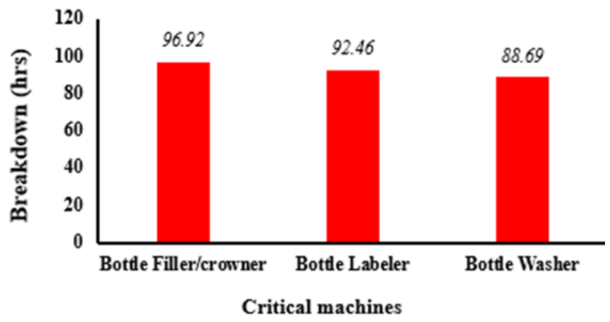

Fig. 1. Top three critical machines on the plant.

Fig. 2. Glass bottle filling and crowning machines

B. Autonomous Maintenance Implementation

As part of restoring the glass bottle filler/crowner machine to its basic operating condition, the machine operators were tasked with continuous monitoring of their equipment and were allowed to make minor adjustments and basic troubleshooting. This was part of establishing an autonomous maintenance (AM) program for the most critical machine with the highest number of breakdown hours. An AM team was set up (5x core machine operators, 1x mechanical specialist, 1x electrical specialist, and 1x supervisor as team leader) for the bottle filler/crowner. This team was responsible for completing and delivering on their machines the seven AM steps as part of the plant reliability improvement program. Figure 3 is a representation of the AM team members.

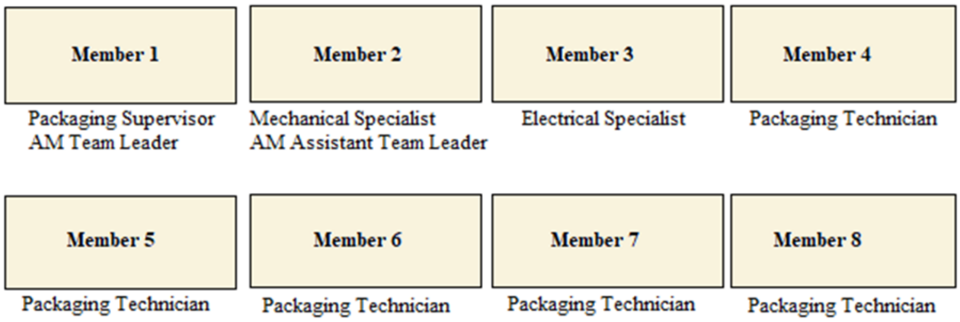

Fig. 3. Autonomous maintenance team members.

The goal of the first step was to increase the basic understanding of machine components and train operators of the critical machine to perform a total cleanout (TCO) and maintenance activities to a certain level. The components of the critical machine, with detailed descriptions of the function of each component, were extracted from the machine operating manual for the operators to be trained on. Based on their training, the operators were then allowed to perform a deep cleaning and minor maintenance on the machine components. A maintenance support technician (electrical or mechanical) was always on standby to attend to more complex maintenance issues. Once the operators understood how machine components worked, with the ownership given back to them to perform minor adjustments as part of the preventive maintenance program, they then developed a vested interest in understanding and accepting the need for step 2 (eliminating sources of dirt) and step 3 (creating cleaning, inspection, lubrication, and tightening standards) more. Machine and component abnormalities were identified along with sources of dirt, difficult to clean and inspect areas. Provisory cleaning and inspection checklists were developed, with clarity on how specific cleaning and inspection tasks would address machine breakdowns and minor stoppages that were affecting machine efficiency. Tags were raised for deteriorated parts that were negatively impacting machine performance. These were then registered in a tag registry and handed over to the PM team for scheduling maintenance. Steps 2 and 3 were easily achievable because the operators and technicians were already equipped with the necessary information in step one. Figure 4 shows the sources of machine dirt for the glass bottle filler/crowner identified under AM step 2.

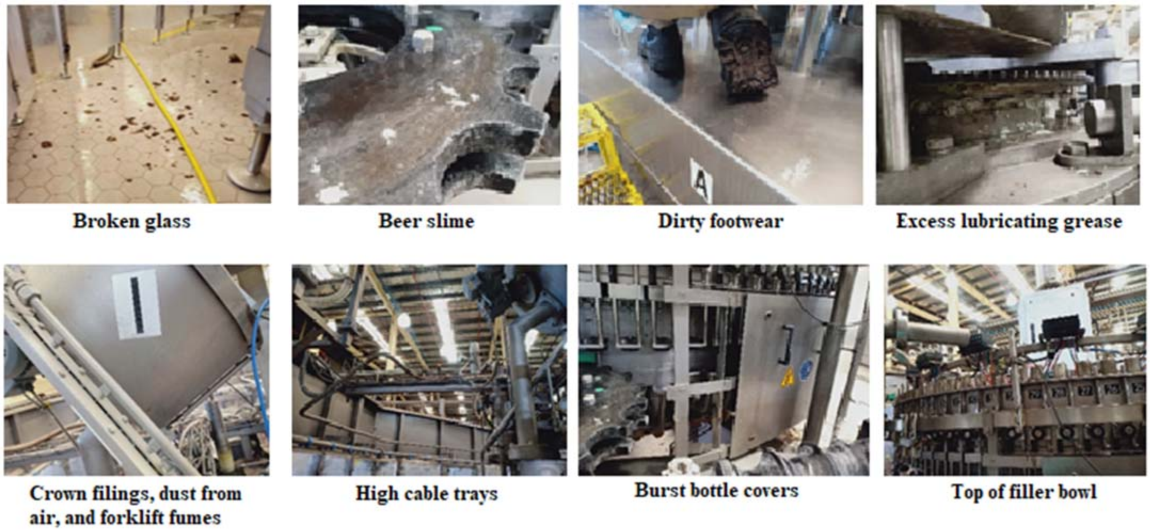

Fig. 4. Sources of dirt identified and eliminated under AM step 2.

Establishing cleaning and routine maintenance standards is step three of the autonomous maintenance program. Based on sources of dirt identified in step two, countermeasures were established through checklists that defined specific actions towards eliminating root causes of defects and performing a routine cleaning of dusty parts. One point lessons (OPLs), cleaning, inspection, lubrication, and tightening (CILT) standards were formulated to prevent equipment deterioration through correct operation and daily checks. The aim was to establish basic conditions needed to keep equipment well-maintained hence improving machine reliability. Steps 1 to 3 of the autonomous maintenance program enabled the operators to develop and master skills in detecting abnormalities in machines, understand the functions and components of the bottle filler/crowner, and recognize possible quality issues on their machines. With these skills, they then established countermeasures to reduce chronic problems, detect and troubleshoot causes of abnormalities, and identify and solve problems affecting product quality.

IV. Results & Discussion

A. Detection of Machine Abnormalities

The starting point for fault detection was a detailed cleaning and inspection of components of the filler/crowner machines. Oil leaks, beer spillages, glass fragments, dust particles, beer slimes, etc surrounding the glass bottle filler/crowner were deep-cleaned and the machine components inspected simultaneously. Any missing pieces such as bolts, nuts, screws, or damaged parts such as guides, conveyor links, hose fittings, cables, etc discovered during the total cleanout (TCO) were tagged at their exact location on the machines. The tags raised were for the deteriorated parts that were negatively impacting machine performance. A machine layout detailing parts and purpose of components at the infeed, main machine, and outfeed of filler/crowner was printed in large boards and made visible on the machine areas. Any abnormality found was marked on the machine layout and a tag was raised, registered in a common tag registry, and handed over to the PM team for scheduling maintenance. By implementing autonomous maintenance, the key operators on the shop floor became more involved in each maintenance operation because they were more engaged in the daily functions of the machine components hence were able to detect abnormalities in the bottle filler/crowner machines. Provisory cleaning, inspection, lubrication, and tightening checklists were then developed, with clarity on how specific cleaning and inspection tasks addressed machine breakdowns and minor stoppages that were affecting machine reliability. Figure 5 shows some of the before and after TCO photos of parts of the glass bottle filler/crowner machine while Figure 6 is the CILT checklist created to prevent component deterioration.

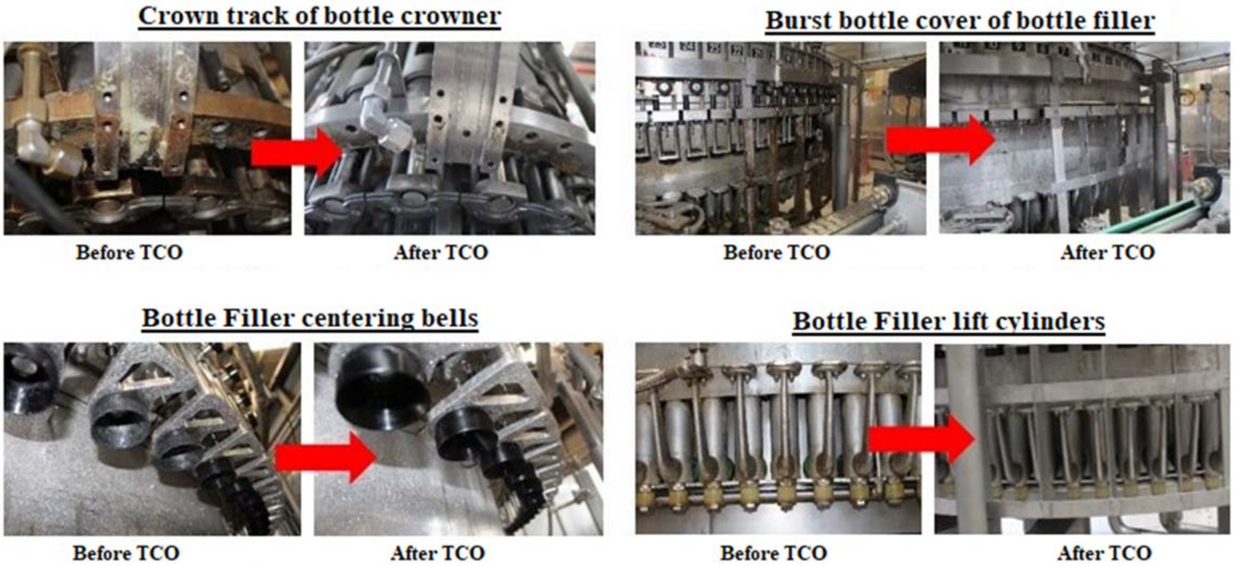

Fig. 5. Photos of filler/crowner components before and after TCO.

BOTTLE FILLER CILT CHECKLIST-DAILY					
				Operator DS:	
Area	**Activity**	**Specification/Standard**	**Equipment**	**Machine Status**	**Time**
1. Safety Door	Check the safety doors	Ensure paneling doors must Open & Close	Hand	STOP	1 min
2. Filler/Crowner	Clean Crowner heads, neck guides, Central star, perspex glass+ Clean Filler lift cylinders, filling valves & ring bowl, format parts & machine surfaces.	Must be free of slime,dirt, bottle fragments and crowns.	Spray gun, Scotching pad	STOP	15 mins
	Remove crowns from crown track before hot water flushing. Also spray water on top of crown track, where dust usually builds up.	Crown track must be cleared	Cotton swab	STOP	10 mins
	Inspect format parts, guides, wear strips and locking pins for wear and tear or defects.	No wear, tear, obstruction or loose bolts.	Hand, Spunner	STOP	1min
3. Filler/Crowner Hot water flushing	Do Hot water flushing with crowner. **NB: Cover up all sensors, solenoids and valves with plastic before flushing.**	Filler/Crowner must be sterilised	HMI	STOP	30 mins
4. Running Inspection	Inspect filling for no overfoaming and underfills	Ensure filling tubes/Deflector/tulip cup not worn,broken, or missing.	Eye		1 min
	b) Process Area - Check air, CO2 valves are open and no leaks along the line. Also inspect infeed sensor if it is operating according to standard.	Air ,CO2, H20 valves open and ensure air pressure is at 6 bar.	Eye		1 min

Fig. 6. Provisory CILT checklist for glass bottle filler/crowner under AM step 3.

B. Improvements in MTBF & MTTR of Critical Machines

The provisory cleaning, inspection, lubrication, and tightening (CILT) checklists created specifically for addressing component abnormalities helped increase machine availability and mean time between failure (MTBF) and contributed towards a significant reduction in mean time to repair (MTTR). Additionally, the number of component breakdowns on the glass bottle filler/crowner was noticeably reduced after implementing autonomous maintenance for two consecutive months from February to

March 2020. Figures 7 and 8 show MTBF and MTTR of the bottle filler/crowner before and after implementing autonomous maintenance, respectively. The results indicate a noticeable increase in MTBF and a decrease in MTTR of the critical machines after implementing AM.

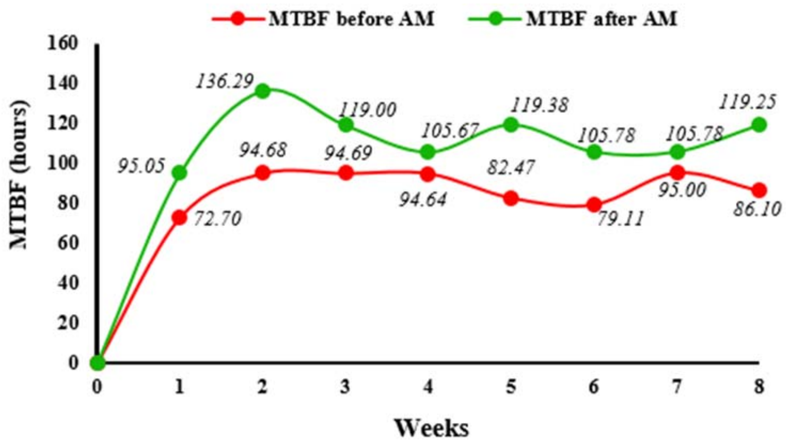

Fig. 7. MTBF of glass bottle filler/crowner before and after autonomous maintenance.

Average MTBF before AM:

$$MTBF\ (ave) = \frac{72.70 + 94.68 + 94.69 + 94.64 + 82.47 + 79.11 + 95.00 + 86.10}{8}$$

$$= 87.42\ hours$$

Average MTBF after AM:

$$MTBF = \frac{95.02 + 136.29 + 119.00 + 105.67 + 119.38 + 105.78 + 105.78 + 119.25}{8}$$

$$= 113.27\ hours$$

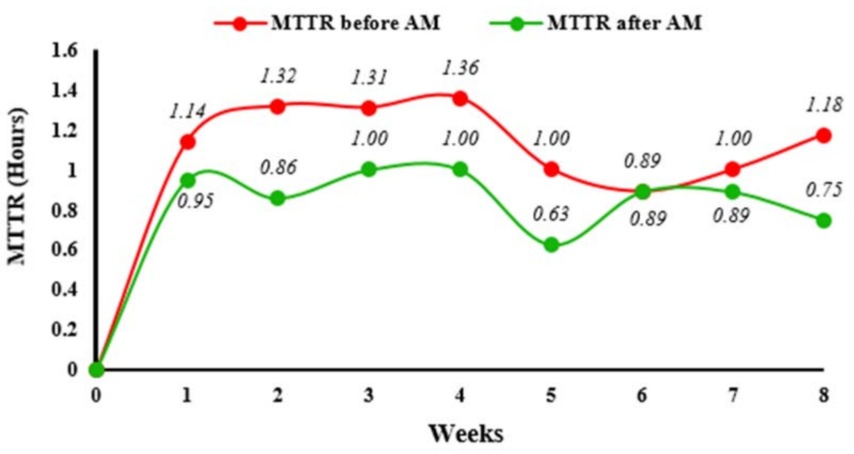

Fig. 8. MTTR of glass bottle filler/crowner before and after autonomous maintenance.

Average MTTR before AM:

$$MTTR\ (ave) = \frac{1.14 + 1.32 + 1.31 + 1.36 + 1.00 + 0.89 + 1.00 + 1.18}{8}$$

$$= 1.15 \text{ hours}$$

Average MTTR after AM:

$$MTTR\ (ave) = \frac{0.95 + 0.86 + 1.00 + 1.00 + 0.63 + 0.89 + 0.89 + 0.75}{8}$$

$$= 0.87 \text{ hours}$$

C. Improvements in Reliability of Critical Machine

The new sense of ownership developed by the operators under the autonomous maintenance program enabled them to keep their machines clean, well-lubricated, and secured. They were empowered to inspect, measure, continuously diagnose abnormalities and take on minor repairs and adjustment responsibilities in problem-solving. The countermeasures developed through provisory cleaning and inspection checklists helped reduce minor stoppages and chronic issues affecting components of the bottle filler/crowner machine. Equipment reliability noticeably increased under the AM program. Figures 9 and 10 show the glass bottle filler/crowner reliabilities at 12 and 24 hours, respectively, before and after autonomous maintenance. Progressive improvements were observed in the overall reliability of the machine.

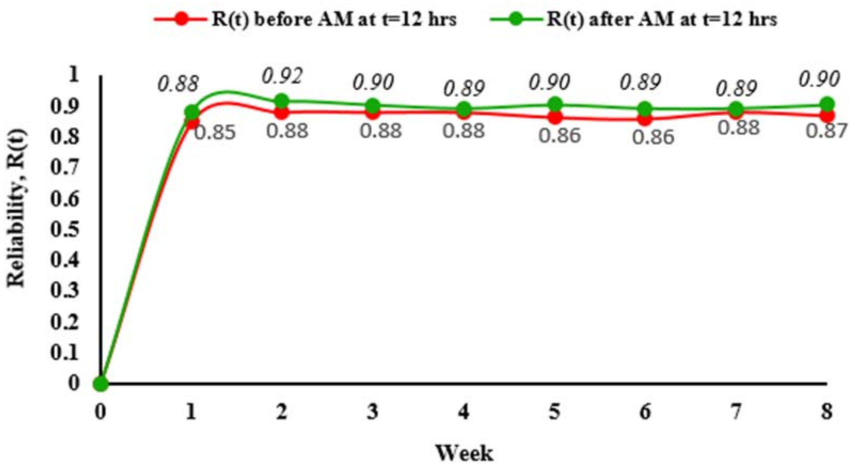

Fig. 9. Reliability of glass bottle filler/crowner before and after AM at t = 12 hours.

Average reliability at t=12 hours before AM:

$$R(12) = \frac{0.85 + 0.88 + 0.88 + 0.88 + 0.86 + 0.86 + 0.88 + 0.87}{8}$$

$$= 0.87$$

Average reliability at t=12 hours after AM:

$$R(12) = \frac{0.88 + 0.92 + 0.90 + 0.89 + 0.90 + 0.89 + 0.89 + 0.90}{8}$$

$$= 0.90$$

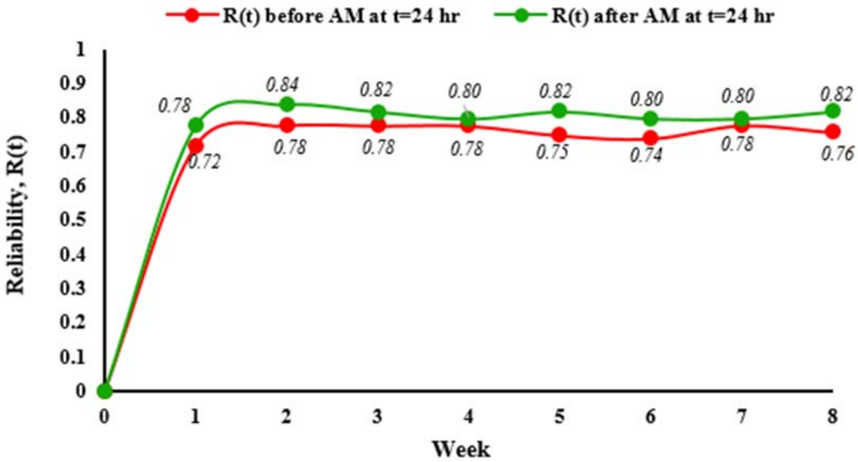

Fig. 10. Reliability of glass bottle filler/crowner before and after AM at t = 24 hours.

Average reliability at t=24 hours before AM:

$$R(24)=\frac{0.72+0.78+0.78+0.78+0.75+0.74+0.78+0.76}{8}$$

$$= 0.76$$

Average reliability at t=24 hours after AM:

$$R(24)=\frac{0.78+0.84+0.82+0.80+0.82+0.80+0.80+0.82}{8}$$

$$= 0.81$$

V. Conclusion

The outcome of this research shows that autonomous maintenance is an important program that can equip machine operators with the right set of knowledge and skills to detect machine abnormalities, optimize equipment performance, reduce downtime, and increase reliability of their machines. The glass bottle filler/crowner, identified as the most critical machine on the plant with 96.92 breakdown hours, was subjected to autonomous maintenance. Before implementing AM, the glass bottle filler/crowner had an average MTBF of 87.42 hours, average MTTR of 1.15 hours, a shift (12 hours) reliability of 87 %, and a complete day (24 hours) reliability of 76 %. After AM implementation, there was a noticeable increase in MTBF to 113.27 hours, a decrease in MTTR to 0.87 hours, and an increase in machine reliability to 90 % and 81 % respectively for 12 and 24 hours operation. These outcomes show that empowering operators in performing autonomous maintenance on their machines is key to detecting equipment failure, reduce breakdown hours, increase reliability, and improve machine and plant performances.

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