

Reliability and Predictive Maintenance Strategies for Wave Welding Machines: Insights from a Case Study

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Abstract—This study investigates reliability and predictive maintenance strategies for wave welding machines, building on previous studies on the DELTA X welding machine. The work focuses on analyzing failure patterns, evaluating maintenance effectiveness, and suggesting improvements based on key operational indicators. Methods such as Pareto analysis, Weibull distribution, and FMEA are employed to identify critical failure modes and optimize maintenance planning. Results show that electrical and heating elements are among the most vulnerable components. Recommendations include implementing preventive and predictive maintenance programs and adopting advanced monitoring technologies. These strategies aim to enhance the reliability, availability, and operational safety of wave welding machines in electronics manufacturing environments.

Keywords—Wave welding machines, Reliability, Predictive maintenance, MTBF, MTTR, Availability, Pareto, Weibull, FMEA

1. Introduction

In modern industrial environments, the maintenance of production equipment is a crucial factor for ensuring operational continuity, product quality, and worker safety. The increasing complexity of manufacturing systems, heightened competition, and stricter regulatory requirements compel companies to adopt optimized and proactive maintenance strategies. Maintenance is no longer limited to reactive repair but now encompasses approaches aimed at preventing failures, maximizing availability, and ensuring operational safety [1, 2].

Reliability-Centered Maintenance (RCM) is a strategic framework that emphasizes the use of performance indicators to continuously monitor equipment condition and anticipate potential failures [3, 4]. In the electronics manufacturing industry, wave welding machines play a critical role in producing printed circuit boards and other components. Implementing predictive maintenance strategies for such machines can significantly improve production efficiency, reduce downtime, and extend equipment lifespan [5, 6].

Several studies have focused on the application of RCM and predictive maintenance in electronics manufacturing. For instance, Aldrini et al. [7] reviewed fault diagnosis and self-healing strategies for smart manufacturing systems, while Lee et al. [8] discussed intelligent maintenance systems and predictive approaches for industrial equipment. Lau and Lee [9] analyzed reliability testing methods for solder joints, providing insight into potential failure mechanisms in wave soldering processes.

This study builds on previous research on the DELTA X welding machine [10] and extends the analysis to derive generalizable reliability and predictive maintenance strategies for wave welding machines. The main objectives of this work are to:

1. Analyze historical failure data and identify the most critical failure modes.
2. Evaluate maintenance effectiveness using indicators such as MTBF, MTTR, availability, and failure rates.
3. Apply Pareto analysis, Weibull distribution, and FMEA to support decision-making for predictive maintenance.
4. Suggest practical improvements to enhance the reliability, availability, and operational safety of wave welding machines.

By systematically applying these methods, this work provides a data-driven roadmap for maintenance managers, allowing for optimized maintenance planning and improved overall performance in electronics manufacturing.

2. Presentation of the Studied Equipment

Wave welding machines are essential in electronics manufacturing, ensuring the reliable soldering of printed circuit boards (PCBs) and electronic components. For this study, the DELTA X welding machine is used as a representative case to illustrate typical operational behaviors, failure modes, and maintenance challenges [10].

These machines integrate several subsystems that directly impact reliability and performance, including:

- Electronic Integration Unit: controls PCB movement, temperature regulation, and wave soldering parameters.
- Conveyor System: ensures precise alignment and transport of PCBs through the soldering process.
- Soldering Bath and Flux Units: maintain a consistent solder wave and flux application.
- Preheating and Temperature Control: prepares PCBs for optimal soldering quality.
- Detection and Monitoring Systems: track potential collisions, misalignments, and component anomalies.

The machine architecture allows for simultaneous processing of multiple PCBs, increasing throughput while maintaining soldering quality. Modern wave welding machines are equipped with advanced software, such as MyWave, for monitoring, logging, and predictive analysis of equipment performance [10]. Figures illustrating the equipment:



Figure 1. Electronic Integration Unit

This unit controls PCB transport, temperature, and wave parameters for optimal soldering performance.



Figure 2. Wave Welding Machine (DELTA X example). *Representative wave welding machine used as a case study for reliability and predictive maintenance analysis [10].*

By using the DELTA X as a benchmark, the study generalizes findings to other wave welding machines in industrial electronics production. The focus is on identifying critical components, understanding typical failure patterns, and evaluating strategies for predictive maintenance.

3. Failure History

To evaluate reliability and plan predictive maintenance, historical failure data of wave welding machines were analyzed. The DELTA X machine, used as a representative example, provides a basis to identify critical components, failure patterns, and downtime distribution [10].

Table 1 summarizes the historical failures and downtime recorded over selected operational periods. The table includes the key subsystems, the time between failures (TBF), the number of failures, and the downtime caused by each failure.

Table 1. Historical Failure Data of Wave Welding Machines (DELTA X as example) [10]

N	Subsystems	TBF (min)	Number of Failures	Downtime (min)
1	Conveyor System	120	4	360
2	Solder Bath	180	3	300
3	Flux unit	300	2	180
4	Preheating	360	2	120

5	Heavy-duty titanium fingers	420	2	60
6	Crash detection	430	1	50
7	Wire feed support	440	1	40
8	PCB tracking systems	450	1	30
9	Mist spray fluxer	455	1	25
10	NitroWave	465	1	15
11	SmartWave	470	1	10

The data indicates that the conveyor system and solder bath are the most critical components, causing the highest downtime. These insights allow for prioritization in preventive and predictive maintenance planning, aligning with strategies highlighted in previous studies [10].

This analysis provides a foundation for subsequent reliability evaluation using Pareto, Weibull, and FMEA methods, which will be presented in the following sections.

4. Forecasting Analysis Method: Pareto 80/20

To identify the most critical subsystems and prioritize maintenance actions, the Pareto 80/20 principle was applied to the failure data of wave welding machines. The method ranks components by their contribution to total downtime, highlighting the 20% of components responsible for approximately 80% of failures [10].

Steps of the Analysis:

1. Collect the Time to Repair (TTR) for each subsystem.
2. Rank TTRs in descending order.
3. Calculate cumulative TTRs and cumulative percentages relative to total downtime.
4. Identify the top contributors to overall downtime for targeted maintenance interventions.

Table 2. Pareto Analysis of Wave Welding Machine Failures [10]

N	Subsystem	Number of Failures	Cumulative Failures	TTR (min)	Cumulative TTR (min)	Cumulative %
1	Conveyor System	4	4	360	360	30.2%
2	Solder Bath	3	7	300	660	55.4%
3	Flux Unit	2	9	180	840	70.6%
4	Preheating	2	11	120	960	80.6%
5	Titanium Fingers	2	13	60	1020	85.7%
6	Crash Detection	1	14	50	1070	89.9%
7	Wire Feed Support	1	15	40	1110	93.3%
8	PCB Tracking	1	16	30	1140	95.8%
9	Mist Spray Fluxer	1	17	25	1165	97.9%
10	NitroWave	1	18	15	1180	99.2%
11	SmartWave	1	19	10	1190	100%

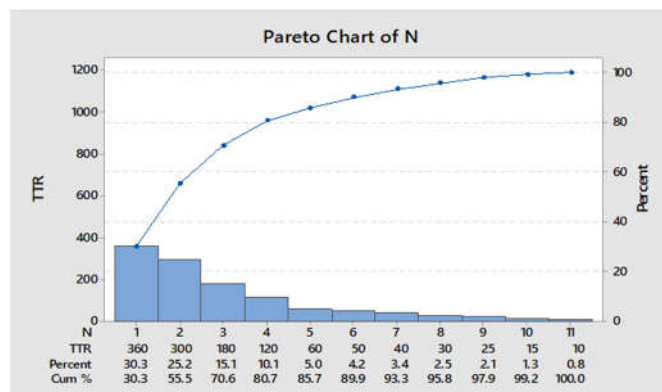


Figure 3. Pareto 80/20 Curve of Subsystem Downtime [10]

The analysis shows that the conveyor system and solder bath are responsible for over 55% of total downtime. Including the flux unit brings the cumulative contribution to 70.6%, confirming that a small number of subsystems account for most failures, consistent with the Pareto principle.

Implications for Maintenance :

- These findings allow maintenance managers to focus preventive and predictive strategies on the most critical components.

- Aligns with data-driven reliability-centered maintenance approaches, reducing unplanned downtime and optimizing operational efficiency [10].

5. Weibull Parameters Calculation

To evaluate the reliability behavior of wave welding machines and to support predictive maintenance strategies, a Weibull statistical analysis was applied to the Time Between Failures (TBF) data of the DELTA X machine, considered here as a representative case study [10]. The Weibull distribution is widely used in reliability engineering because of its flexibility in modeling different failure mechanisms.

5.1 Weibull Modeling of Time Between Failures

The TBF data were sorted in ascending order. The cumulative failure probability was estimated using the median rank method, expressed as:

$$F(i) = \frac{i - 0.3}{N + 0.4}$$

where:

- i is the failure order,
- N is the total number of failures.

The Weibull distribution function is defined as:

$$F(t) = 1 - R(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^\beta}$$

where:

- β is the shape parameter,
- η is the scale parameter,
- γ is the location parameter.

Using Minitab software, the estimated Weibull parameters are:

$$\beta = 4.18, \quad \eta = 410.41 \text{ min}, \quad \gamma = 0$$

Table 3. Actual Distribution Function of TBF

N°	TBF (min)	N	$\sum n_i$	F(i)	F(i) %
1	470	1	1	0,0486	4,86
2	465	1	2	0,1180	11,80
3	455	1	3	0,1875	18,75
4	450	1	4	0,2569	25,69
5	440	1	5	0,3263	32,63
6	430	1	6	0,3958	39,58
7	420	1	7	0,4652	46,52
8	360	1	8	0,5347	53,47
9	300	1	9	0,6041	60,41
10	180	1	10	0,6736	67,36
11	120	1	11	0,7430	74,30

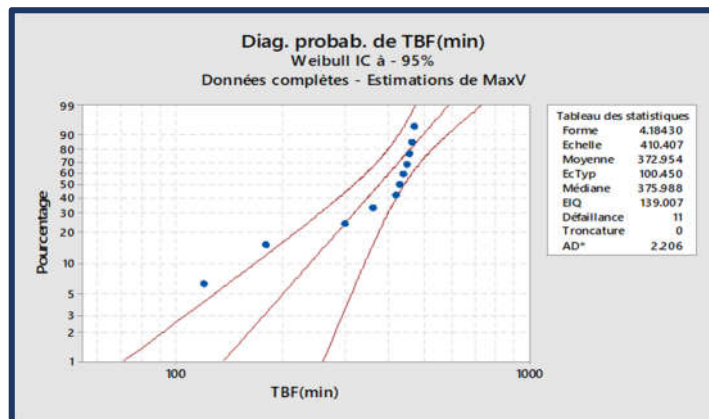


Figure 4. Weibull Probability Plot (Minitab Software)

The value $\beta > 1$ indicates a wear-out failure mode, where the failure probability increases with operating time.

5.2 Probability Density and Failure Distribution

The probability density function (PDF) is given by:

$$f(t) = \frac{\beta}{\eta} \left(\frac{t - \gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^\beta}$$

Table 4. Probability Density Function f(t)

TBF (min)	120	180	300	360	420	430	440	450	455	465	470
f(t)x10 ⁻³	2,2	7,1	28,1	37,6	36,4	35	33,3	31,4	30,3	28,1	26,9

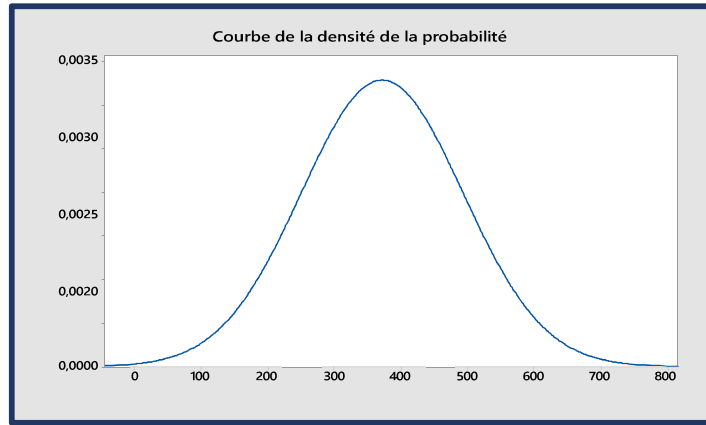


Figure 5. Probability Density Curve

The PDF shows an increasing trend until higher operating times, indicating progressive degradation of critical components.

The cumulative distribution function (CDF) represents the probability that a failure occurs before time t:

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^\beta}$$

Table 5. Cumulative Distribution Function

TBF	470	465	455	450	440	430	420	360	300	180	120
F(t)	0,82	0,81	0,78	0,77	0,73	0,7	0,66	0,43	0,23	0,03	0,0058

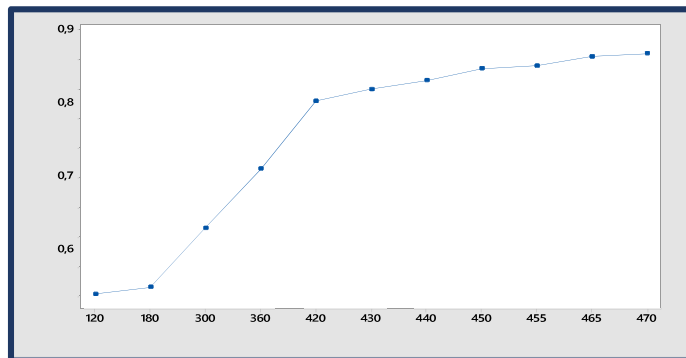


Figure 6. Cumulative Distribution Function Curve

5.3 Reliability Analysis

The reliability function is defined as:

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^\beta}$$

Table 6. Reliability Function R(t)

TBF	120	180	300	360	420	430	440	450	455	465	470
R(t)	0,99	0,96	0,76	0,56	0,33	0,29	0,26	0,22	0,21	0,18	0,17

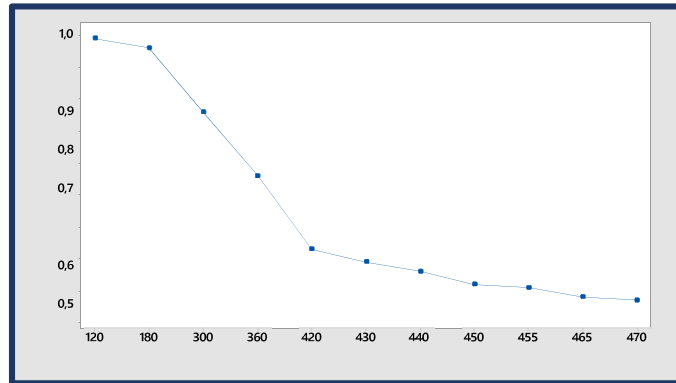


Figure 7. Reliability Curve

At the Mean Time Between Failures (MTBF), reliability is moderate, indicating a critical operating period where predictive maintenance actions should be scheduled.

5.4 Failure Rate Analysis

The failure rate (hazard function) is expressed as:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta} \left(\frac{t - \gamma}{\eta} \right)^{\beta-1}$$

Table 7. Failure Rate Function $\lambda(t)$

TBF (min)	120	180	300	360	420	430	440	450	455	465	470
$\lambda(t)$	0,0002	0,0007	0,003	0,006	0,010	0,011	0,012	0,013	0,014	0,015	0,016

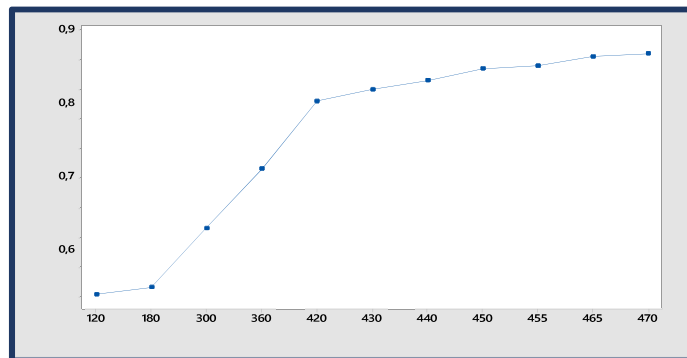


Figure 8. Failure Rate Curve

The increasing failure rate confirms that the equipment mainly operates in a wear-out phase.

5.5 Maintainability Analysis

The Mean Time To Repair (MTTR) is calculated as:

$$MTTR = \frac{\sum TTR}{N}$$

The repair rate is defined as:

$$\mu = \frac{1}{MTTR}$$

The maintainability function is given by:

$$M(t) = 1 - e^{-\mu t}$$

Table 8. Maintainability Function M(t)

TTR	10	15	25	30	40	50	60	120	180	300	360
M(t)	0,147	0,212	0,328	0,379	0,470	0,548	0,614	0,851	0,942	0,991	0,996

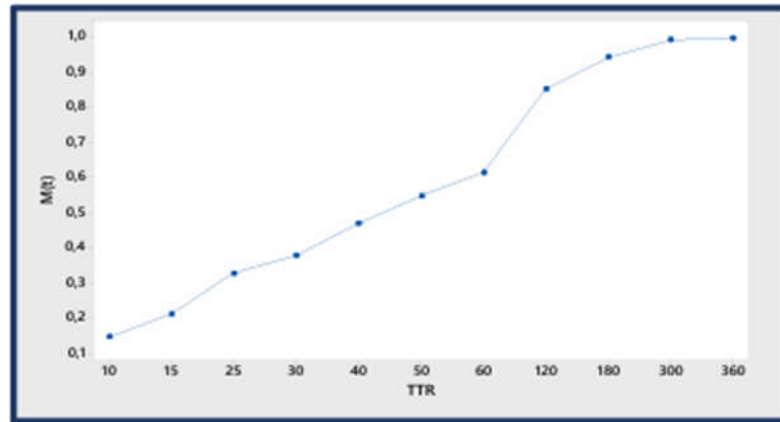


Figure 9. Maintainability Curve

The curve shows a rapid increase in maintainability, followed by saturation.

5.6 Availability Analysis

The instantaneous availability is calculated using:

$$D(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda + \mu)t}$$

Table 9. Availability Function

T(h)	10	20	30	40	50	60	70	80	90	100	110
D(t)	6,05	6,03	6,01	6	5,99	5,98	5,97	5,96	5,95	5,94	5,93

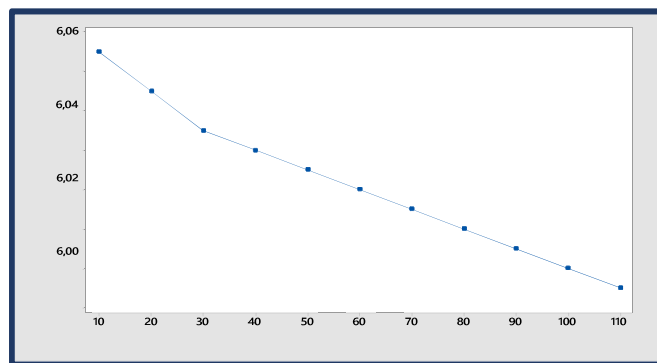


Figure 10. Availability Curve

The availability decreases progressively with time, highlighting the impact of increasing failures and maintenance actions.

5.7 Implications for Predictive Maintenance

The Weibull-based analysis provides actionable insights for predictive maintenance:

- Identification of wear-out periods before critical failures
- Optimization of maintenance intervals
- Prioritization of critical subsystems
- Improvement of availability and operational safety

6. FMEA: Failure Modes and Effects Analysis

To systematically identify potential failures, their causes, and impacts on wave welding machines, a Failure Modes and Effects Analysis (FMEA) was conducted. This method supports predictive maintenance strategies by highlighting the most critical subsystems that require attention [10].

Table 10. FMEA of Wave Welding Machine Subsystems [10]

Subsystem	Function	Failure Modes	Causes	Effects	Detection	O	S	D	C	Recommended Actions
Conveyor System	Guide and transport PCBs	Misalignment, belt slip	Wear, improper tension, crashes	Poor board alignment, welding defects	Visual	6	7	5	210	Regular maintenance, belt tension adjustment
Solder Bath	Provide molten solder	Contamination, oxidation	Inadequate cleaning, debris	Weld bridges, defective joints	Visual	5	8	4	160	Frequent inspection, bath filtration and cleaning
Flux Unit	Apply flux evenly	Clogging, irregular deposition	Flow quality issues, nozzle blockage	Excessive/insufficient flux, defective seals	Visual	4	6	6	144	Clean nozzles, check flow quality
Preheating	Even heating of boards	Uneven heating, overheating	Heater failure, temperature regulation issues	Thermal stress, welding defects	Visual	5	7	5	175	Inspect heating elements, calibrate regulation system
Titanium Fingers	Transport boards	Damage, misalignment	Wear, crashes, debris	Transport problems, solder defects	Visual	4	6	5	120	Replace damaged fingers, preventive maintenance
Crash Detection	Detect collisions	Sensor failure	Faulty sensors, software issues	Potential machine damage, safety risk	Alarm	3	9	3	81	Test sensors, update software, preventive maintenance
PCB Tracking	Track board position	Tracking failure	Software issues, sensor faults	Misalignment, defective soldering	Visual	4	7	5	140	Verify and calibrate sensors, update software
Mist Spray Fluxer	Spray flux	Clogging, irregular flow	Nozzle blockage	Excessive/insufficient flux	Visual	4	6	6	144	Clean nozzles, check flow quality
NitroWave / SmartWave	Generate optimal wave	Component failure, calibration issues	Wear, misadjustment	Welding defects	Visual	5	8	4	160	Regular calibration and adjustment of machine parameters

Notes on FMEA Metrics:

- Occurrence (O): Probability of the failure happening.
- Severity (S): Impact on system, safety, or quality.
- Detection (D): Likelihood of detecting the failure before it causes damage.
- Criticality (C): Product of $O \times S \times D$.

The FMEA highlights that the conveyor system and solder bath are the most critical subsystems, consistent with the Pareto and Weibull analyses. Focusing maintenance and monitoring efforts on these components maximizes predictive maintenance effectiveness and operational safety.

7. Conclusion

This study presented an in-depth analysis of the reliability and predictive maintenance strategies for wave welding machines, building on previous work on the DELTA X welding machine [10]. Through the application of Pareto analysis, Weibull distribution, and FMEA, key reliability indicators such as MTBF, MTTR, availability, and failure rates were evaluated, identifying the most critical subsystems requiring focused maintenance.

The results indicate that conveyor systems, solder baths, and flux units are responsible for the majority of failures and downtime. Implementing targeted preventive and predictive maintenance programs, combined with real-time monitoring, can significantly enhance machine availability, reduce unplanned downtime, and improve overall production quality.

Limitations: This study focused on a single machine type and a specific set of operational data, which may limit generalization to other welding machines or production contexts. Additionally, long-term operational validation of predictive maintenance strategies was not performed.

Future Perspectives

1. Expand the analysis to multiple machines across different production lines to improve generalizability.
2. Integrate IoT-based predictive monitoring and machine learning algorithms for real-time failure prediction.
3. Assess the economic and environmental impact of optimized maintenance strategies, including energy consumption and resource usage.
4. Develop digital twins of wave welding machines to simulate maintenance scenarios and optimize scheduling.

These perspectives aim to promote sustainable, efficient, and safe industrial operations, while continuously improving reliability and production performance.

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