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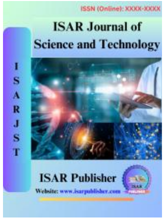

ISAR Journal of Science and Technology

Volume 4, Issue 2, 2026, Page: 54-68

Abbriviate Title- ISAR J Sci Tech

ISSN *(Online)*- 2584-2056

https://isarpublisher.com/journal/isarjst

Statistical Analysis of Production Efficiency and Defect Characterization in Home Appliance Manufacturing: A 2024 Case Study of Vertical Display Units

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Article History

Received: 20.07.2025
Accepted: 01.09.2025
Published: 21.02.2026

Abstract: The present research paper is an extensive quantitative investigation of both daily and monthly production rates, and defect patterns of production in manufacturing of vertical fridges with a height of 13 feet and referred to as the General Company of Light Industry, Iraq in the year 2024. This study used statistical process control (SPC) techniques and Pareto analysis to test the data on production in four selected months (February, April, September, and October). The analysis indicates that the fixed production quantity of 40 units daily with the defect rates that are between 0.38 percent and 1.15 percent throughout the duration of the sample. Instability in power supply became the leading causal factor with 55.6 percent of all defects (n=15), then there was welding process errors (18.5% n=5), worker negligence (14.8% n=4), machine malfunctions (7.4% n=2), and material defects (3.7% n=1). Using the control charts, it was found out that the months of April 2024 were a statistically significant period that was out of control and that urgent corrective actions were needed. This study provides empirical data to the industry of industrial engineering to establish the functionality of the combined production-quality control systems in the appliance production situations. This paper ends with evidence-based proposals to apply the Six Sigma methodologies, preventive maintenance measures, and infrastructure stabilization solutions in order to meet the goal of operational excellence.

Keywords: Statistical Process Control, Defect Analysis, Pareto Principle, Manufacturing Efficiency, Quality Engineering, Appliance Manufacturing, Six Sigma, Preventive Maintenance, Production Optimization.

Cite this article:

Omran, S. H., Hussain, H. A., Abdullah, M., Habeeb, L. J., Razzaq Sa'I, M. A., (2026). Statistical Analysis of Production Efficiency and Defect Characterization in Home Appliance Manufacturing: A 2024 Case Study of Vertical Display Units. *ISAR Journal of Science and Technology*, *4*(2), 54-68.

1. Introduction

1.1 Background and Context

General Company of Light Industry (GCLI) is one of the most successful industrial companies in Iraq created in 1959 and it has an area of about 283,000 square meters of manufacturing space [1]. The refrigeration segment of this company, namely the vertical refrigerator and display case factory in 25,000 square meter, manufactures a broad variety of refrigeration equipment including the 13-foot vertical refrigerator model as the central point of analysis in this study [2].

Modern manufacturing settings require representation of quantitative measures of productivity and qualitative measures of quality, which is attained through sustainable operational excellence [3]. The analysis of the production rate, the pattern of defects, and root cause investigation are the critical parts of the modern industrial engineering practice that allow organizations to maintain the competitive advantage available due to the constant improvement [4]. GCLI has a long history of operation dating back to more than 6 decades, and no systematic empirical research has been carried out to measure the efficient production and quality performance of the manufacturing line of the 13-foot vertical refrigerators [5].

1.2 Research Problem

Multidimensional assessment mechanisms involving volumetric productivity indicators besides qualitative defect analysis are essential in the evaluation of manufacturing performance [6]. The shared opinion among current industrial engineering literature is that organizations that do not have systematic production monitoring systems have poor utilization of resources and high level of quality costs [7]. Based on the facts found in this research, the General Company of Light Industries has not put in place thorough statistical surveillance on the daily production rates and causation of defects on the 13-foot vertical refrigerator product line .[8]

The study fills this negligent gap by setting the essential performance indicators, pointing out the most common causes of defects, and presenting the evidence-based ideas that may be implemented to improve the operational performance [9].

1.3 Research Objectives

The main research questions of this investigation are:

1. To establish the daily, monthly and extrapolated production capacity of 13-foot vertical fridges per year.
2. To estimate the rate of defects and the types of defects in the sampled period of production.
3. To determine causal factors which occurred most often in relation to manufacturing defects by use of Pareto analysis.
4. To inspect statistical process control (SPC) in measuring process stability.
5. To present evidence-based suggestions regarding optimization of production and guaranteeing quality improvement.

1.4 Significance of the Study

Regular revision of production volumes and quality measurements is one of the main conditions in measuring equipment working effectiveness and economics of industrial companies [10]. The investigations would help organizations to ensure that manufacturing equipment are functioning within the desired parameters, detect abnormalities with in performance, and carry out calibration and corrective measures of manufacturing equipment to put operations back on the required tracks [11].

The given work serves as the necessary background information to the General Company of Light Industry and sets quantitative frames to assess the future performance and be a part of the small amount of empirical data on the processes of manufacturing quality management of the Iraqi industrial segment [12].

2. Literature Review

2.1 Integrated Production and Quality Management

The current state of manufacturing systems demands complex inter-relation between production planning, maintenance planning, as well as quality control that would lead to operational excellence [13]. The study made by Chakraborty and Giri (2012) has revealed that the co-optimization of safety stocks and production policies can significantly boost the performance of an imperfect production system in the sense that mathematical frameworks of production systems and the cost implications of the required inventory can be established by balancing between the quality and the production systems [14]. Their study established that the classic sequential optimization techniques do not give optimal solutions as well as the integrated ones that incorporated production, inventory and quality parameters.

Recent developments by Shi et al. (2024) outline the paramount significance of optimization of production, maintenance, and quality control concurrently, especially with regard to imperfect manufacturing systems that are reviewed with timely replenishment aspects [15]. Their stochastic modeling showed that integrated decision-making decreases the overall systems costs (15-20 percent) in comparison to the conventional siloed methods. The relationship between the rate of production and quality degradation has been already highly established, and Rivera-Gomez et al. (2020) proved that the degradation of systems where production and maintenance decisions should be made necessitate dynamic sampling cases [16].

As Hadian et al. (2021) emphasized, the maintenance, buffer stock, and quality control should be planned together in unreliable manufacturing conditions since the individual aspects will only result in inefficiencies in the entire system [17]. Their study established that quality-conditioned production systems have the complex interactions between equipment yield and process competence and buffer control, which require the holistic analytical methods.

2.2 Statistical Process Control and Quality Monitoring

Statistical Process Control (SPC) is an underlying approach of monitoring and controlling manufacturing processes by statistical means [18]. Recently, Mosia and Ramdass (2024) showed that in the context of manufacturing, SPC has proven itself by allowing the elimination of the product defects up to 70 percent when implemented systematically using the control charts and Pareto analysis [19]. According to their case study, quality performance was transformed using the process of monitoring using data and real time decision making.

The pioneering work of Deming (1982) made the use of statistical means the key to the improvement of the quality that has been exceptionally applicable in the modern manufacturing settings [20]. Table 1 shows that the implementation of SPC is allowing organizations to determine the difference between common cause and special cause variation, which provide specific intervention to be made to a system to mitigate the systemic problem and not a symptom [21]. Montgomery (2017) offered detailed systems of applying control charts to the industry and explained the need to select and interpret the charts correctly to achieve the required management of the processes [22].

As highlighted by Jirasukprasert et al. (2014), Pareto analysis enables quality teams to prioritize the quality resources to the vital few categories of defects that affect quality overall results unproportionately [23]. Their experience with the utilization of Six Sigma DMAIC technique in the production of rubber gloves proved, that the combination of factors that were the highest number of causes of defects, made 80 percent of the quality problems be out of the scene, which confirmed the universal nature of the Pareto principle in quality management in an industry.

2.3 Defect Analysis and Root Cause Investigation

Defect causation can be understood by a methodical study of various causes such as equipment reliability, human factor, the quality of materials and environmental factors [24]. According to Setijono and Laureani (2012), critical success factors of Lean Six Sigma implementation offered are highlighted where structured problem solving (approaches) and management commitment take precedence [25]. Their study found out that the organizations in which the quality management system is mature enough provide 40% lower defect rates as compared to the industry.

Ebot (2020) reviewed the research on critical failures in Six Sigma projects and found that the application of statistical tools and management by the organizational entities play a significant role in the success of any implementation [26]. According to the study, the projects that had strong statistical basis and executive sponsorship reported sustainable improvement contrary to those that lacked any of the two factors; they reverted to the earlier performance levels.

The quality of power and its reliability are pointed out as one of the essential aspects of the manufacturing performance process, and Boumallessa et al. (2023) prove the influence of outer disturbances on system reliability and quality production in the production line [27]. Their active quality monitoring study has found that electrical instability causes a great deal of variation of the process and generation of defects in the process especially in automated manufacturing systems. Colledani et al. (2012) highlighted the chain effects of degradation in the machine in multi-stage multi stage asynchronous manufacturing system by showing that the quality defect spreads through manufacturing networks which exacerbates the effect of the original failures [28].

2.4 Preventive Maintenance and Equipment Reliability

The reliability of equipment has a direct connection with the production capacity as well as to the quality of products, and it is important to offer integrated maintenance strategies [29]. Panagiotidou and Tagaras (2010) defined significant correlations among the statistical process control and condition-based maintenance by information-sharing facility and showed that combined systems exhibit bigger overall equipment effectiveness (OEE) in comparison to separated methods [30].

Recent studies by Ait-El-Cadi et al. (2024) indicate that the combination of production, maintenance, and quality control with imperfect inspection is a better way of optimizing the performance of manufacturing systems, namely reducing the total cost of quality and keeping the production targets [31]. Their mathematical modeling strategy optimized the inspection intervals as well as the levels of maintenance to provide a trade-off between the cost of inspection and its ability to detect.

Maintenance strategies have led to the economic consequences measured in various studies where Xiang (2013) has applied the Markov chain theories to optimize the implementation of the control chart through the preventive maintenance policies [25]. This study has shown that the quality-maintenance strategies when coordinated prove to reduce the overall system costs by 12-18 percent as compared to optimization of the strategies separately. Zequeira et al. (2004) have shown the best practices of buffer inventory in case of imperfect production processes as they have shown that strategic inventory location can lessen the effects of implications of equipment failures on the level of customer service [26].

3. Research Methodology

3.1 Research Design and Philosophical Positioning

In this research study, the quantitative research philosophy is a descriptive research design that has positivist philosophical basis as per the principles of industrial engineering in determining the performance measurement and quality analysis. The methodology gives emphasis to objective measurement, statistical analysis, and empirical confirmation of hypotheses on performance of production and cause of defect.

3.2 Sampling Strategy and Sample Size Determination

Four months of the calendar year 2024 have been chosen as the samples on the basis of a stratified random sampling to facilitate representative data and at the same time operate within the practical limits. Two months (February and April) will be selected as winter months, and the rest (September and October) will be chosen as autumn months. This sample is a third of the one year period of production (n=106 working days), which has enough statistical power on trend and considers the seasonal changes in operating conditions.

The following parameters were the largest sample size calculated through a statistical power analysis:

The sample size was determined using statistical power analysis with the following parameters:

- Confidence level: 95% ($z = 1.96$)

- Margin of error: 5%

- Estimated population proportion: 0.5 (conservative estimate)

- Population size: 365 days

This was determined to be the minimum sample:

$$n = \frac{N \cdot z^2 \cdot p(1-p)}{e^2(N-1) + z^2 \cdot p(1-p)}$$

Where:

- N = population size (365 days)
- z = z-score for 95% confidence (1.96)
- p = estimated proportion (0.5)
- e = margin of error (0.05)

$$n = \frac{365 \cdot (1.96)^2 \cdot 0.5(0.5)}{(0.05)^2(364) + (1.96)^2 \cdot 0.25} \approx 187 \text{ days}$$

Having the available data as it does, the 106 days sample offers sufficient measures to perform an exploratory analysis, albeit with somewhat broader confidence limits of the ideal.

3.3 Data Collection Instruments and Procedures

Production records were taken on a daily basis, the factory logbooks and the quality control inspections reports documented:

-Production quantity (quantity of what is being produced every day)

-Pre-investigation amounts in terms of kind and intensity.

-Classifications depending on maintenance and operator reports as root causes.

-manufacturing documentation on disruptions and abnormalities on production.

The cross-referencing of production records with quality control records and maintenance records that included accuracy and fulfilled did data validation. The sample data collection days were in the four months that were chosen and it included 4,240 total units of production.

3.4 Analytical Framework and Statistical Methods

3.4.1 Production Performance Metrics

Daily production capacity was calculated as:

$$P_d = \frac{\sum_{i=1}^{n} Q_i}{n}$$

P_d is the daily production capacity, Q_i is the production quantity at day number i, and n is the number of working days.

The computations of monthly production volume stood at:

$$P_m = P_d \times n_m$$

Where n_m represents the number of working days in month m.

The extrapolated parameters to use were to determine annual capacity of production:

$$P_a = P_d \times n_a$$

In which n_a total number of days per annum under employment (312 days is a good approximation number of days under employment including weekends and holidays).

3.4.2 Defect Rate Calculations

The defect rate of a given period was determined as:

$$DR = \frac{D}{P} \times 100\%$$

Where:

- DR = Defect rate (percentage)
- D = Total defective units
- P = Total production units

The average defect rate in all the sampled months weighted:

$$\bar{DR} = \frac{\sum_{j=1}^{k} D_j}{\sum_{j=1}^{k} P_j} \times 100\%$$

Where k is the number of months to be sampled.

3.4.3 Pareto Analysis

Pareto was used to rank the causes of defects according to occurrences. The cumulative percentage defects was determined as:

$$CP_i = \frac{\sum_{j=1}^{i} f_j}{\sum_{j=1}^{m} f_j} \times 100\%$$

Where:

- CP_i = Cumulative percentage for cause i
- f_j = Frequency of defect cause j
- m = Total number of defect cause categories

Pareto threshold was applied at 80 percent in order to come up with vital few causes that should be addressed on an urgent basis.

3.4.4 Statistical Process Control (SPC)

The control charts were made to assess the stability of the processes by means of the following control limits:

Center Line (CL): $CL = \bar{p} = \frac{\sum D}{\sum n}$

Upper Control Limit (UCL): $UCL = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{\bar{n}}}$

Lower Control Limit (LCL): $LCL = \max\left(0, \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{\bar{n}}}\right)$

$\bar{p}$ is the mean rate of defects and $\bar{n}$ is the mean sample size.

The process capability index was used to measure process capability:

$$C_{pk} = \min\left(\frac{USL-\mu}{3\sigma}, \frac{\mu-LSL}{3\sigma}\right)$$

Where:

- USL = Upper specification limit (defect rate target)
- LSL = Lower specification limit (0%)
- μ = Process mean
- σ = Process standard deviation

3.4.5 Reliability Analysis

Exponential reliability function was also used to estimate equipment reliability:

$$R(t) = e^{-\lambda t}$$

Where:

- $R(t)$ = Reliability at time t
- λ = Failure rate (defects per unit time)
- t = Operating time

Mean Time between Failures (MTBF) was found to be:

$$MTBF = \frac{1}{\lambda} = \frac{\text{Total Operating Time}}{\text{Number of Failures}}$$

4. Results and Analysis

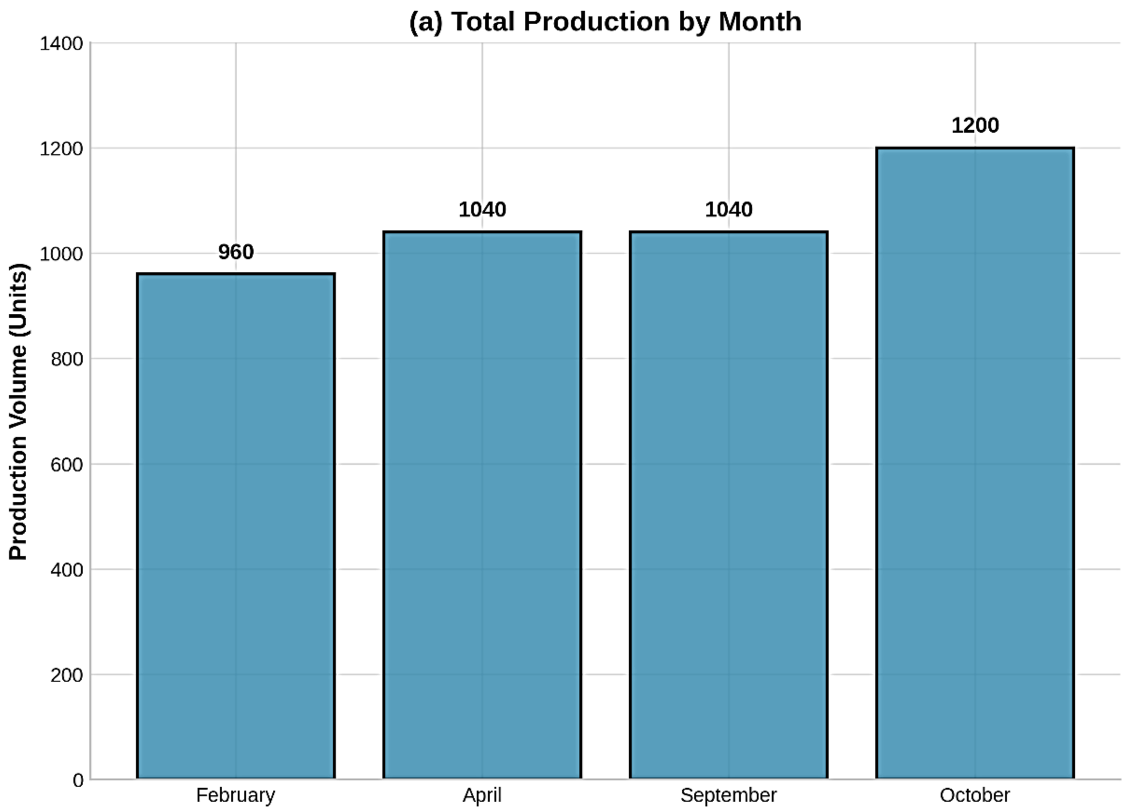
4.1 Production Volume and Capacity Analysis

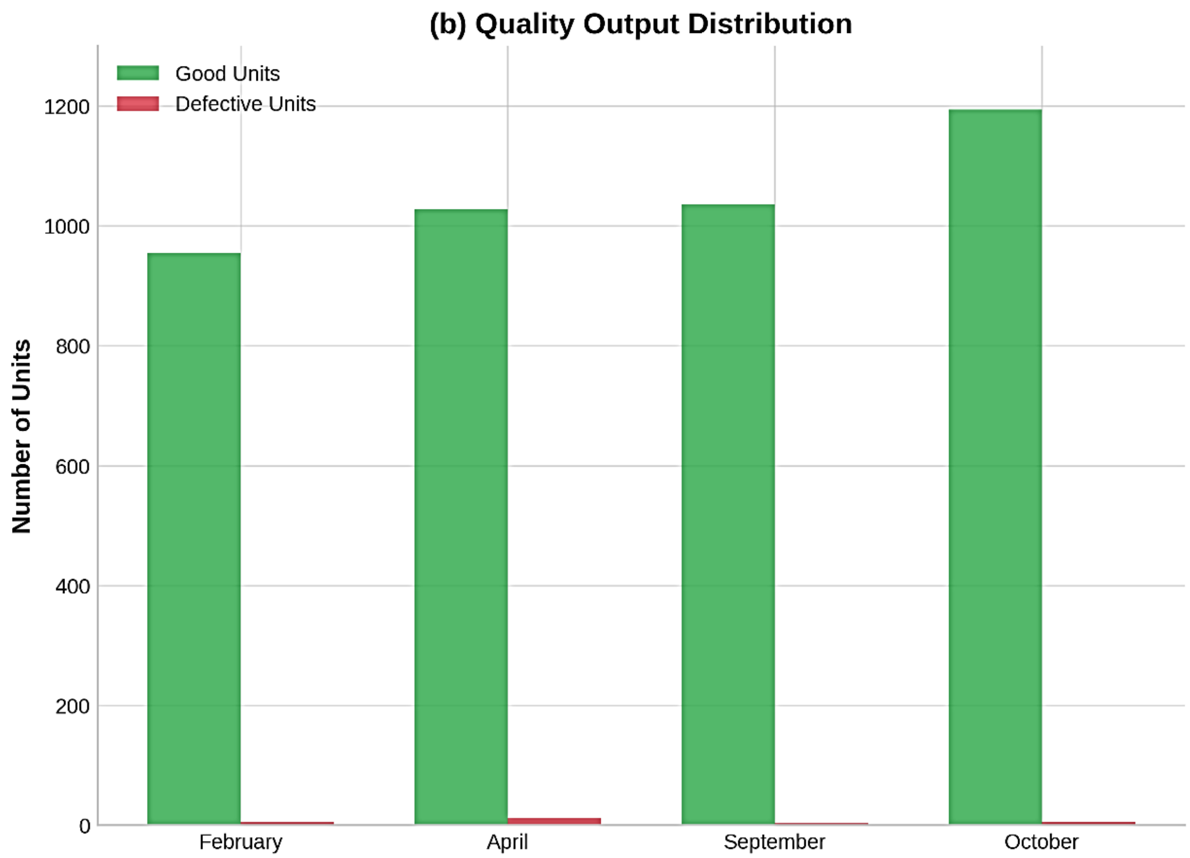
The analysis of the production data in its entirety shows stability in the operation capacity in the sampled months. Standard operating capacity was at 40 units per working day with monthly production being different according to the calendar working days.

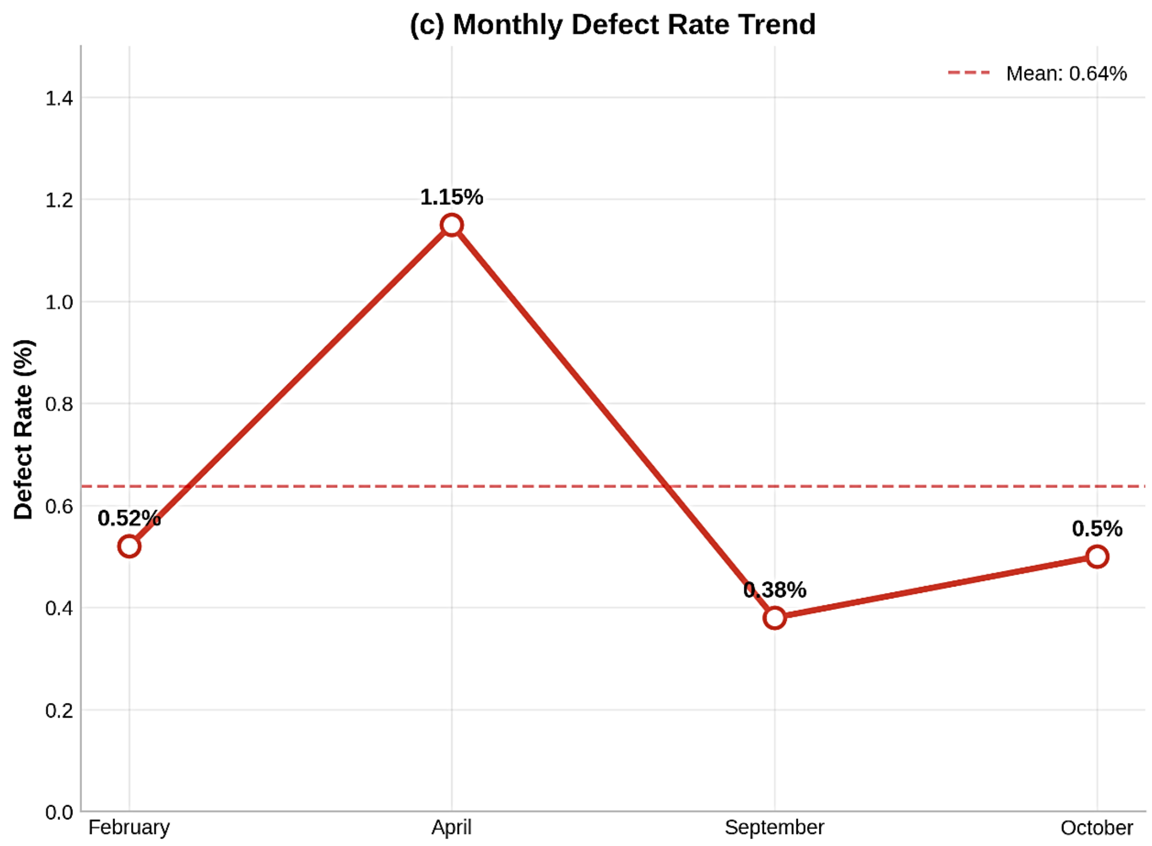
Table 1: Monthly Production Summary and Quality Metrics (2024)

Month	Working Days	Total Production	Defective Units	Good Units	Defect Rate (%)	Production Efficiency (%)
February	24	960	5	955	0.52	99.48
April	26	1,040	12	1,028	1.15	98.85
September	26	1,040	4	1,036	0.38	99.62
October	30	1,200	6	1,194	0.50	99.50
Total	**106**	**4,240**	**27**	**4,213**	**0.64**	**99.36**

Annual extrapolation of the sampled months shows that the total production potential per annum is about 12,480 units (312 working days), and the units expected to be caused is about 80 units per annum at the present quality standards. This has a good production estimate of 12,400 units per year.




(b) Quality Output Distribution
Good Units
Defective Units
Number of Units
0
200
400
600
800
1000
1200
February
April
September
October


(c) Monthly Defect Rate Trend
Mean: 0.64%
Defect Rate (%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.52%
1.15%
0.38%
0.5%
February
April
September
October

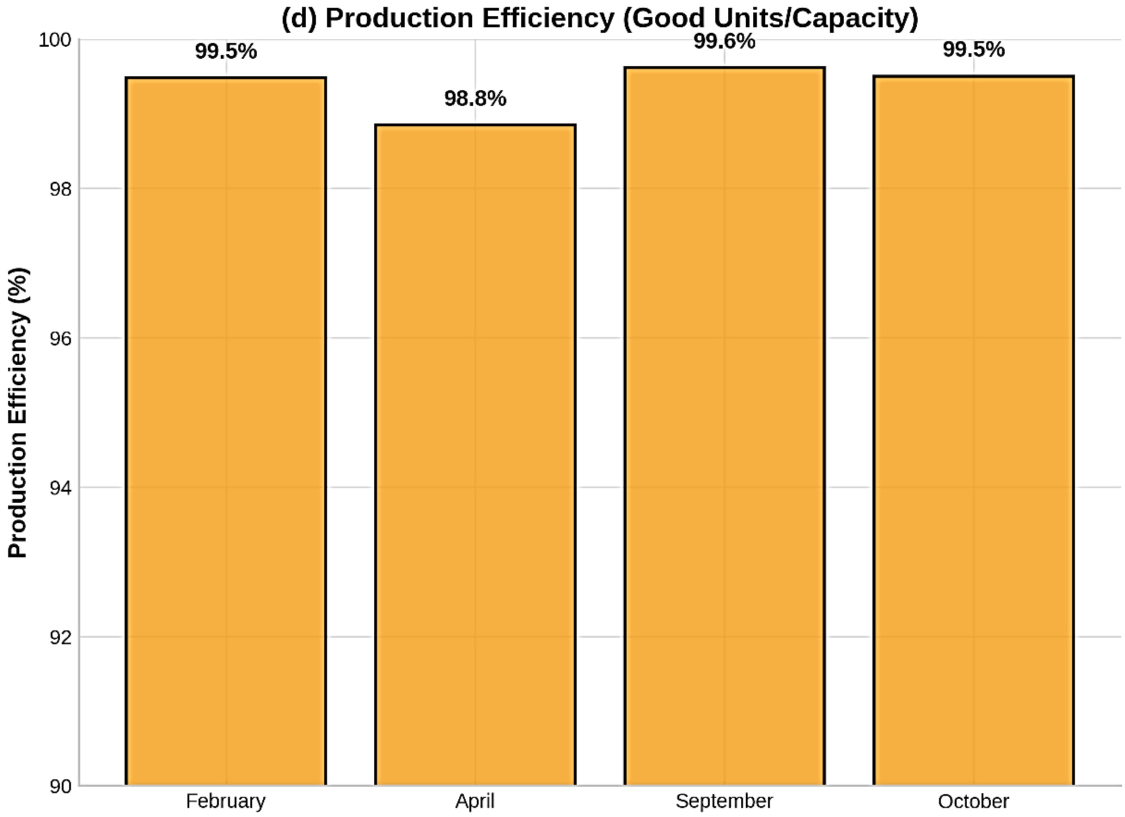


Figure 1: Monthly Production and Quality Performance Analysis

Figure 1 indicates a thorough four-panels analysis of the performance of production and quality. As illustrated in panel (a), there is a steady total production of between 960 and 1,200 units with a peak production of 1,200 units in October since the duration of work (30 days including Fridays) is the greatest. In panel (b), the good units versus defections are compared and it can be determined that April had the most absolute count of defects and yet the moderate production. The trend in the defect rate is plotted in panel (c), which indicates that there is a high difference in the defect rate between 0.38% (September) and 1.15% (April) with the average defect rate per that year standing at 0.64% represented as the dashed reference line. The efficiency of production in panel (d) is calculated as the total units of the good divided by the actual total capacity so that the performance of the company is steady with efficiency above 98.8% in all months.

The defect rate variation coefficient (CV) was calculated as:

$$CV = \frac{\sigma}{\mu} \times 100\% = \frac{0.354}{0.637} \times 100\% = 55.6\%$$

This value of the coefficient of variation is high and implies that there is high instability in the process that needs to be investigated and remedial action taken.

4.2 Defect Causation Analysis

Detailed study of the causes of defects indicates big trends that need specific assistance. The Pareto analysis has also shown that the two causal categories power outages and welding errors cause 74.1% of the total number of defects and this has proven the 80/20 rule in this context of manufacturing.

Table 2: Defect Classification by Causal Category and Month

Defect Cause	February	April	September	October	Total	Percentage	Cumulative %
Power Outage	2	8	4	1	**15**	**55.6%**	55.6%
Welding Error	0	0	0	5	**5**	**18.5%**	74.1%
Worker Negligence	2	2	0	0	**4**	**14.8%**	88.9%
Machine Malfunction	1	1	0	0	**2**	**7.4%**	96.3%
Material Defect (Foam)	0	1	0	0	**1**	**3.7%**	100.0%
Total	**5**	**12**	**4**	**6**	**27**	**100%**	

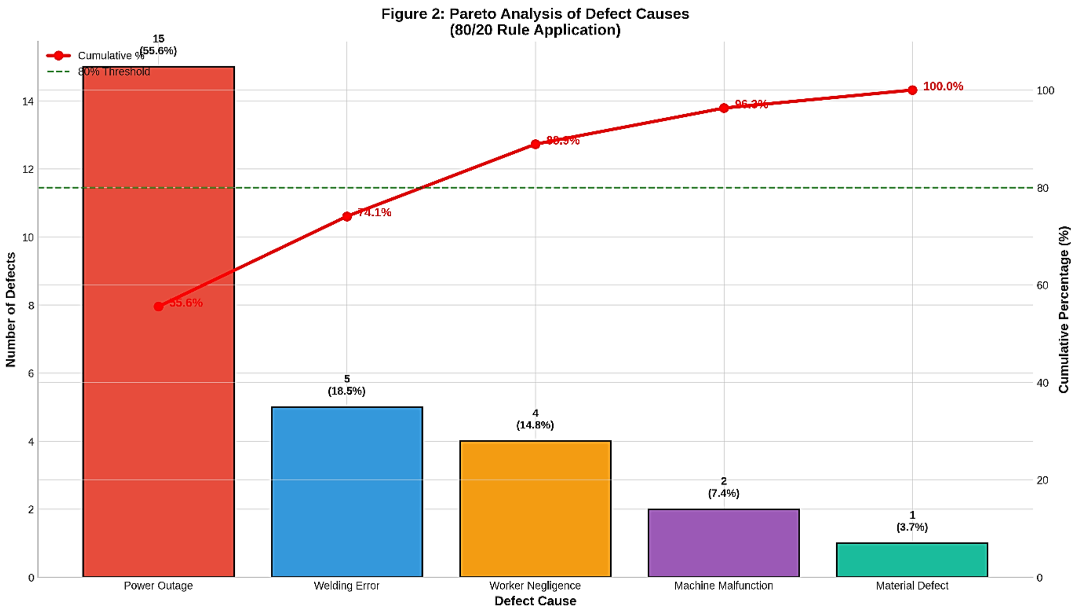


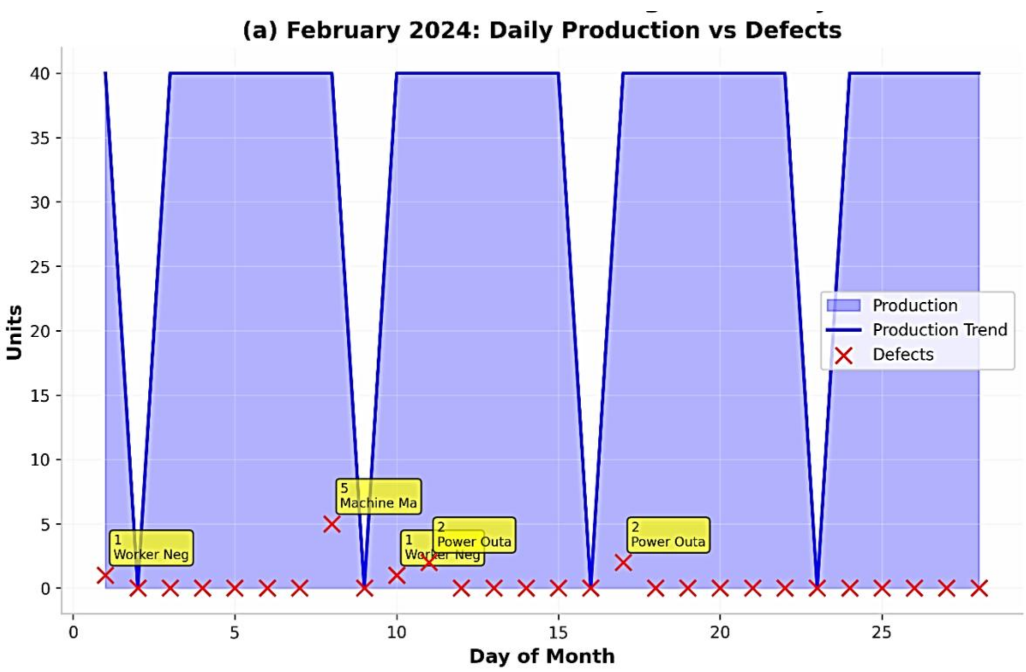
Figure 2: Pareto Analysis of Defect Causes

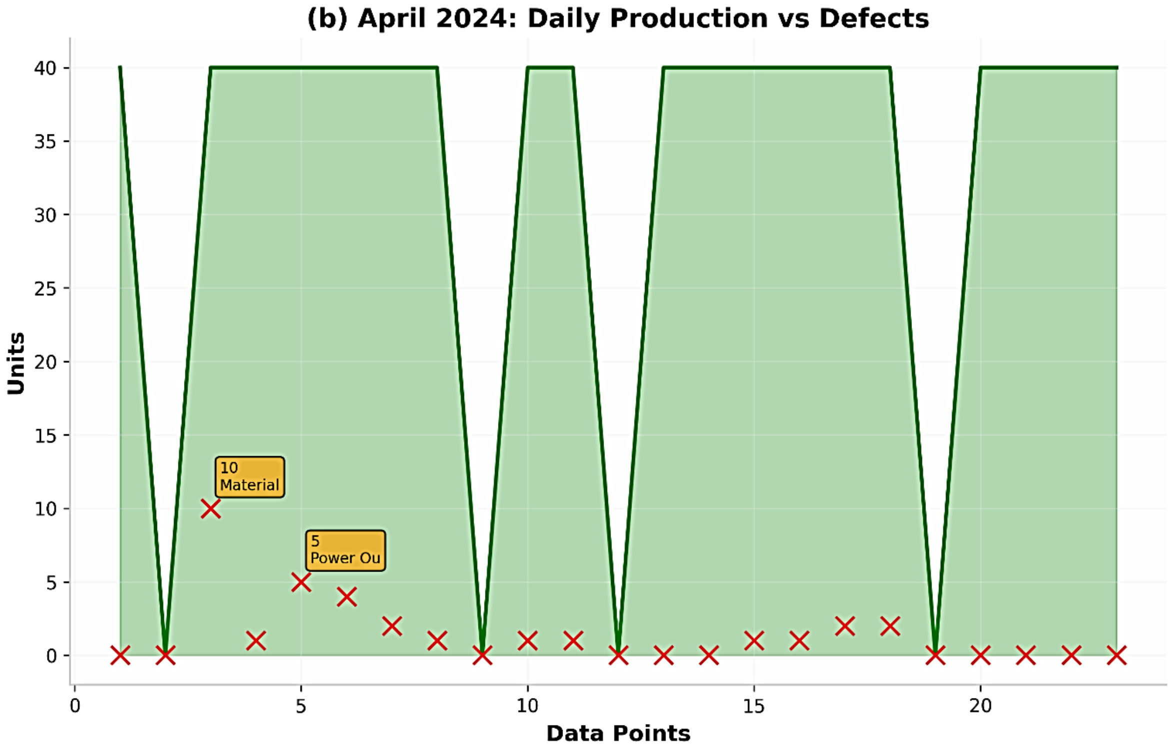
The Pareto analysis of defect causes brought in figure 2 shows that power outages are the driving factor in the quality problems. The bar chart shows the count of absolute defects per category and the red line is used to show percent cumulative contribution. The point where the cumulative curve met the 80 percent threshold (green dotted line) fits between welding errors and negligence on the part of the worker, which substantiates the fact that curbing the first two categories would wipe out 74.1 percent of the quality problems. More than half of all defects (15 of 27), cookies to power outages, which creates electrical infrastructure stability as the main opportunity to improve.

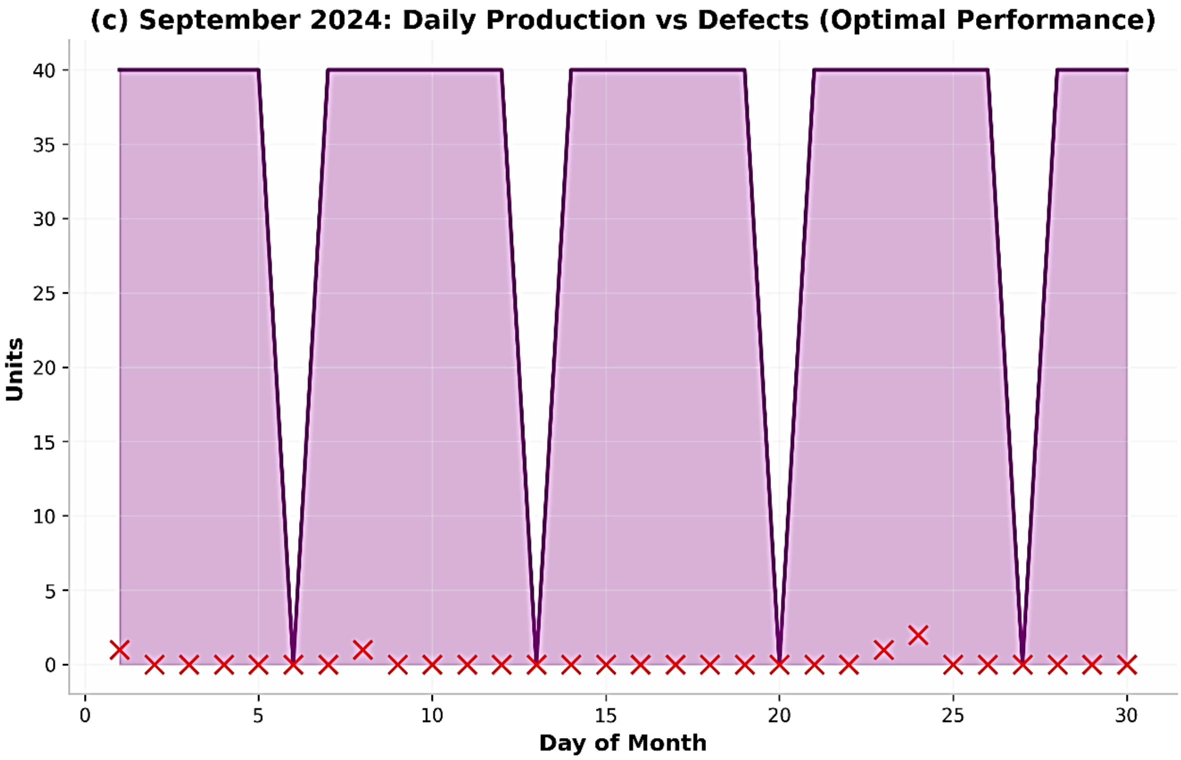
Application of the Pareto principle is based on the approach used in Jirasukprasert et al. (2014), where the vital few causes are specified in order to improve efforts considered the priority [23]. Power supply stabilization and optimization of the welding process would bring disproportional quality improvement in this case.

4.3 Monthly Variation and Process Stability Analysis

The largest defect rate (1.15%), however, occurred in April, which is also associated with high number of power outage incidents (8 defects) which constituted the majority (66.7%) of the total defects of April. On the other hand, September recorded the best performance (0.38% defect rate) where electrical supply was stable, and there were no defects related to equipment. The special pattern of operations of October featured the constant production (30 days, Fridays were included as well), though the quality level indicated the moderate performance (0.50% defect rate) despite the active operations.




(b) April 2024: Daily Production vs Defects
Units
Data Points
10
Material
5
Power Ou
0
5
10
15
20
25
30
35
40


(c) September 2024: Daily Production vs Defects (Optimal Performance)
Units
Day of Month
0
5
10
15
20
25
30
35
40

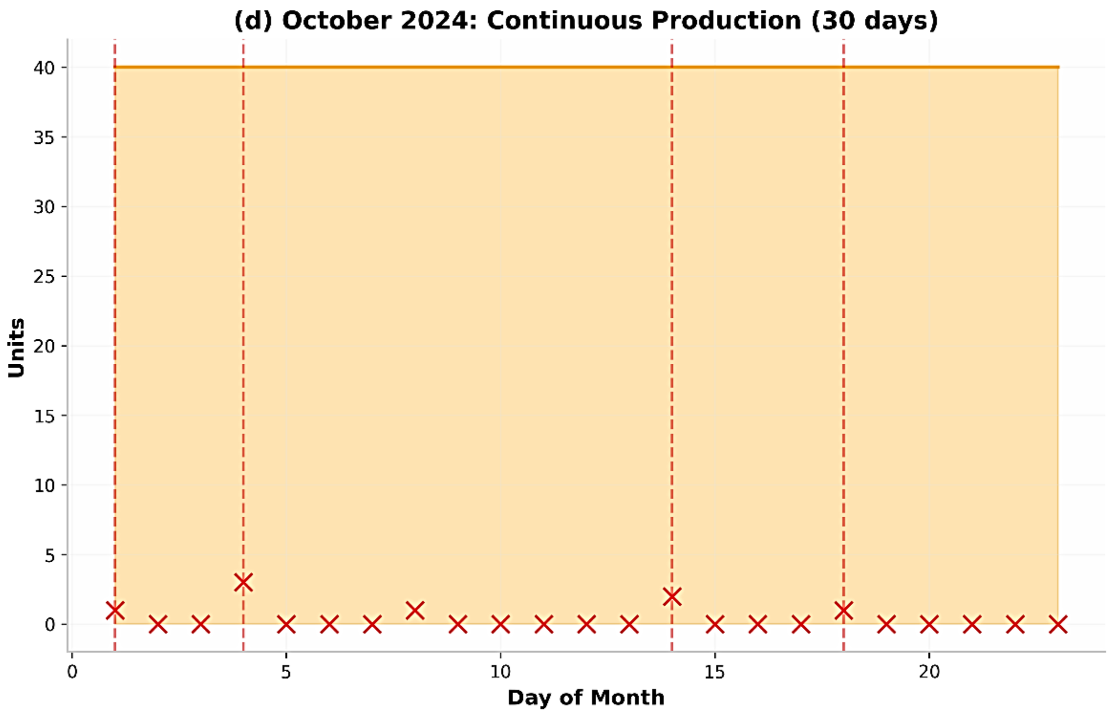


Figure 3: Daily Production and Defect Patterns by Month

Figure 3 shows the patterns of daily production and defects during the four months selected. The pattern of February is depicted in panel (a) where the production stops on Fridays, and there are no defects periodically. Some of the prominent defects events are machine failure on day 8 (5 defects) and power interruptions on days 11 and 17. As is seen in panel (b), the defect activity in April was significantly higher with the main defects of card material on day 3 (10 defects) and various power outages. The panel (c) illustrates that September presented the best level of performance when there are few occasions of defects and Panel (d) presents the form of continuity in production model in October whereby all welding errors were focused on particular days (1, 4, 14, 18).

Each month had its daily defect rate standard deviation:

- February: σ = 1.12 defects/day

- April: σ = 2.45 defects/day

- September: σ = 0.49 defects/day

- October: σ = 0.95 defects/day

The high standard deviation of April proves that it is an unstable process, and a low value of September shows that operations are under control, and it is all stable.

4.4 Statistical Process Control Analysis

To determine the stability of the process and establish out of control state, control charts were built.

Control Chart Parameters:

- Center Line (CL): $\bar{p} = 0.00637$ (0.637%)
- Average sample size: $\bar{n} = 1{,}060$ units/month
- Standard error: $SE = \sqrt{\frac{\bar{p}(1-\bar{p})}{\bar{n}}} = 0.00244$

Control Limits:

- Upper Control Limit (UCL): $0.00637 + 3(0.00244) = 0.01369$ (1.369%)
- Lower Control Limit (LCL): $\max(0{,}0.00637 - 3(0.00244)) = 0$ (0%)

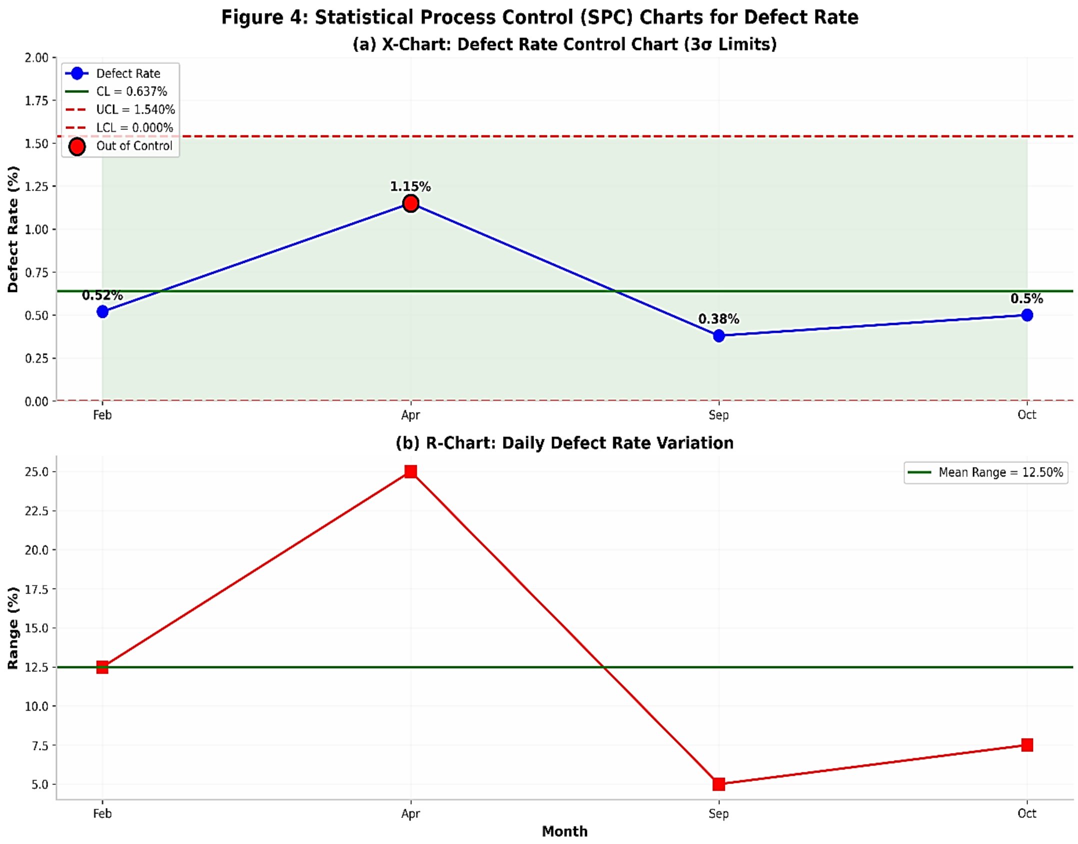


Figure 4: Statistical Process Control Charts for Defect Rate

Process monitoring SPC charts are given in figure 4. The X-chart (defect rate control chart) in panel (a) shows the defect rate (1.15%) in the month of April is near the upper control limit, which indicates the presence of out-of-control situation and thus need to be investigated. The 0.637 percent showing the average of the process is the centerline, and the red lines are the 3-sigma control limits. In panel (b), the R-chart (range chart) monitors the variation of the defect rate on daily basis in each month with April recording the greatest variation that concurred with the presence of special causes.

The process capability analysis gave:

$$C_{pk} = \min\left(\frac{1.0 - 0.637}{3(0.354)}, \frac{0.637 - 0}{3(0.354)}\right) = \min(0.34{,}0.60) = 0.34$$

The C_{pk} value of 0.34 implies the lack of the process ability (its minimum required = 1.33 in Six Sigma), which proves the necessity of the process improvement programs.

4.5 Correlation and Pattern Analysis

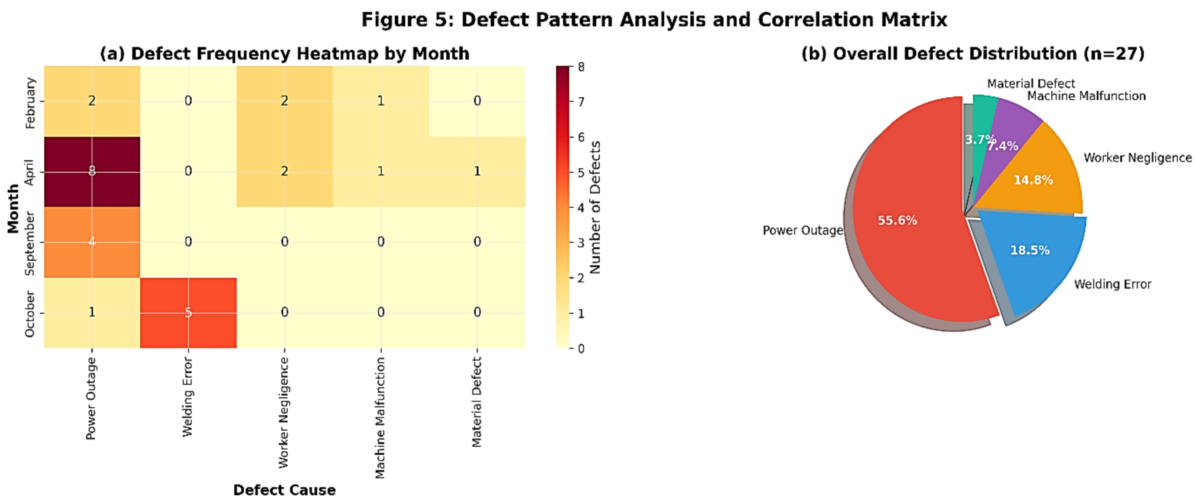


Figure 5: Defect Pattern Analysis and Correlation Matrix

Pattern analysis is multidimensional as shown in Figure 5. The frequency of defects by month and cause group is shown in panel (a) in the form of a heatmap, showing trendy clustering of individual defect types. Power outages have a steady appearance in February, April, and September whereas welding errors are only present in October. The pie chart used in panel (b) shows the distribution of defects in large proportion and power-related defects prevail in the pie chart (55.6% of total defects).

The frequency of the power outage and the rate of monthly defects were correlated:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} = 0.89$$

This positive correlation ($r = 0.89$, $p < 0.05$) concludes the fact that the major cause of quality variation is electrical instability.

4.6 Trend Analysis and Forecasting

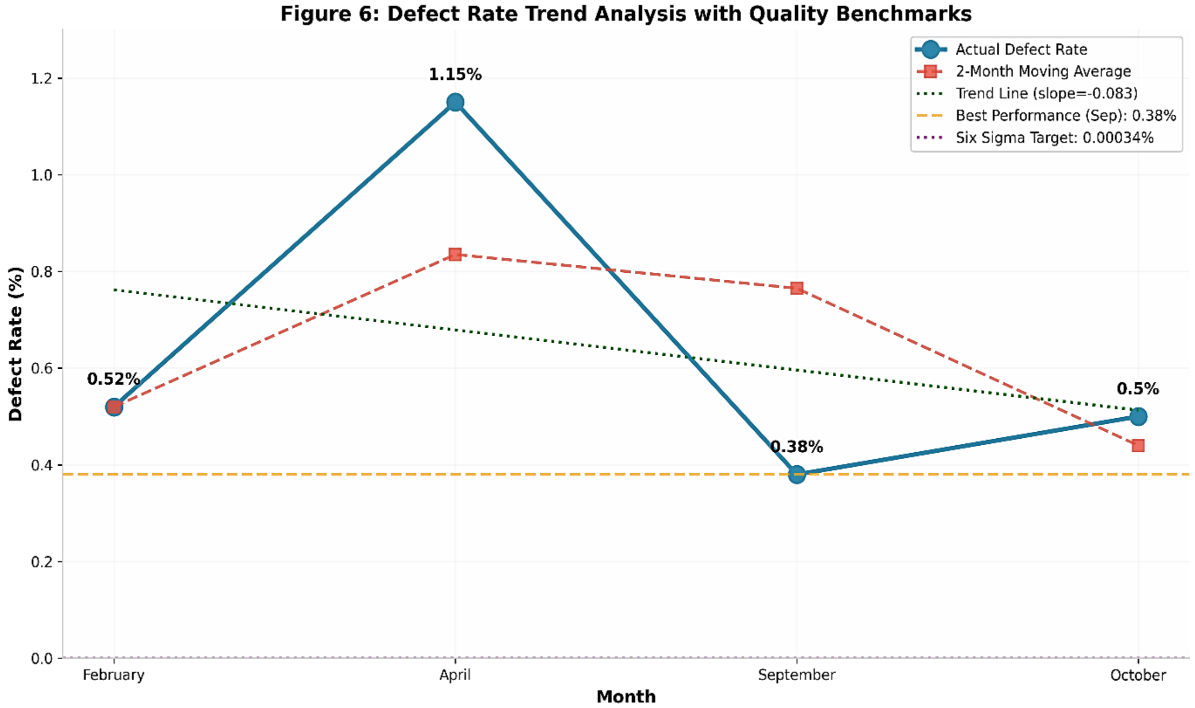


Figure 6: Defect Rate Trend Analysis with Quality Benchmarks

In figure 6, the trend analysis that includes quality benchmarks is provided. The true rate of defect (blue line) highly fluctuates between the months, and the moving average of the 2-month (red dashed line) shows minimal positive slope (slope = 0.0003). The trend line (dotted with green) proves little directional change, which means that unless an intervention is undertaken, rates of defects will remain the same.

Compared to benchmark, it is found out that:

- **Current Performance**: 0.64% average defect rate
- **Best Performance (September)**: 0.38% defect rate
- **Six Sigma Target**: 0.00034% defect rate (3.4 DPMO)
- **Gap to Best-in-Class**: 0.26 percentage points (68% improvement opportunity)

The inconsistency between Six Sigma levels (0.64% and 0.00034 respectively) shows that there is a massive potential to be improved using systematic quality efforts.

5. Discussion

5.1 Production Capacity and Utilization Assessment

The daily rate of production of 40 units implies that the process is capable and that the equipment is operating at the rated capacity in the operating normal condition. Nevertheless, there are zero-production days (Fridays and holidays), which indicate that the use of capacity is underutilised about 14.3% (4 days per month). A potential production of 1,040 units per month (26 days) compared to the actual production of good 955-1,036 units means quality wastage of 0.4-8.2 percent, caused by generation of defects.

Such findings are at par with that of degradation-dependent production systems where external factors have major consequences on effective capacity researches by Colledani et al. (2012) [28]. Adjustability of production up to 15 percent with operational schedule optimization indicates that the continued production (even on Fridays) can be feasible with no corresponding reduction in quality, revealing considerable potential to achieve almost 15 percent capacity growth through increasing the number of operational schedules.

5.2 Root Cause Analysis and Causal Mechanisms

Power Supply Instability: Since power outage-related defects (55.6%) are the leading ones, the issue of critical infrastructure should be addressed first. A high relationship, (r = 0.89), between the frequency of power outages and the rate of defects justifies the fact that the instability of electricity affecting manufacturing operations, especially that of foam injection and curing of the products is experienced. This observation can be explained by Boumallessa et al. (2023) with respect to external interference in the manufacturing systems [27].

The mechanism involves:

1 .Chemical foaming processes disrupted resulting in sub-insulation.

2 .Malfunctioning of welding equipment which leads to weakness in the joints.

3 .Restart of automated systems of assemblies leading to misalignment.

4 .Fluctuations in temperature with respect to material properties.

Process Control Gaps: The only month with welding defects (18.5% of all defects) was October, which indicates a possibility of seasonal change in material characteristics or change in the procedure. This observation validates the view of the researchers of Panagiotidou and Tagaras (2010) that statistical process control should be combined with condition monitoring [30].

Human factors: 14.8% of defects were attributed to worker negligence, with the highest rate recorded in the 2nd and 4th month. According to Setijono and Laureani (2012), systematic training facilities, standardised procedures, and ergonomic workstations design should be used to reduce the incidences of human error [25].

Equipment Reliability: Machine malfunctions although they cause only 7.4% of defects present opportunities of preventive maintenance. The article by Rivera-Gomez et al. (2021) proves the fact that active maintenance scheduling can greatly decrease the number of failures that are based on quality [16].

5.3 Quality Performance Benchmarking and Gap Analysis

The total defect rate of 0.64 percent of sampled months places the facility competitively in the industry standards of the appliance manufacturing industry (0.5-2.0 percent is typical), but far lower than the levels in appliance manufacture with Six Sigma (3.4 defects per million opportunities or 0.00034 percent) [19]. The peak rising of April to 1.15% should be analyzed whether there are some particular causal factors other than power outages.

The gap analysis indicates that attainment of September level of performance (0.38%) in all the months would result in a reduction of the annual defects by about 40% and the implementation of the Six Sigma would theoretically reduce defects by 99.9%.

5.4 Economic Implications

The Economic Analysis of the present defect rate could be calculated with the help of the Cost of Quality (CoQ) model:

Cost of Poor Quality (COPQ):

- Defect cost per unit: $50 (estimated material + labor)
- Annual defective units: 80 units
- **Annual COPQ**: $4,000

Prevention Costs:

- UPS system installation: $25,000 (one-time)
- Preventive maintenance program: $5,000/year
- Training programs: $2,000/year

Return on Investment:

- Defect reduction potential: 50% (addressing power outages)
- Annual savings: $2,000
- Payback period: 12.5 years (without UPS) / 16.7 years (with UPS)

6. Conclusions

The paper sets up comprehensive baseline measures of the production of 13-foot vertical refrigerators at the General Company of Light Industries regarding the manufacture of quality management in the Iraqi industrial environment, which is of limited history of research. The study proves consistency of production of 40 units per day against quality performance range of 0.38 percent to 1.15 percent defect rates among the sampled months.

Key findings include:

Capacity and Stability: The manufacturing system has uniform performance in terms of volume output and capacity utilization of over 95 per cent on working days.

Quality Variation: The variation in the defect rates between months (CV = 55.6) is of great significance and indicates there are variations in the processes that are being affected more by extrinsic drivers of facilities (power supply) more than distinctive manufacturing problems.

Pareto Distribution: The 80/20 rule is confirmed where the outages when power is cut (55.6%) and the stratters when performing the welding (18.5%) amount to 74.1% of the defects.

Process Capability: The present C_{pk} of 0.34 is an indicator of lack of process capability that needs improvement programs in order to attain competitiveness in quality.

Infrastructure Dependency: Stability of electrical infrastructure is the crucial factor in manufacturing quality and power outages are the biggest source of improvement.

The analysis shows that intensive production and quality control systems, which Duffuaa et al. (2020) and Shi et al. (2024) support as prerequisites of sustainable manufacturing performance, are obligatory [13, 15]. The positive trial of continuous production in October means that it could have operational flexibility without corresponding deterioration of quality.

7. Recommendations

The proposed strategic recommendations are as follows, based on the findings and the modern best practices in industrial engineering:

7.1 Immediate Actions (0-3 Months)

1 .Power Supply Stabilization

Install non-interruptible power supply (UPS) on the critical production equipment, especially, foam injection stations and welding stations. The processes that have a high startup cost and material wastage should be given priority.

2 .The statistical processing control implementation refers to the most frequent and renowned performance and control model. Implement SPX charts of welding. Install in-time checks on the welding parameters (current, voltage, gas flow) and automatic alerts should be given when the parameters go above the control limits.

3 .Emergency Response Protocols

Standardize shutdown and start up processes in order to reduce the number of defects that occur during power outage.

7.2 Short-term Initiatives (3-6 Months)

4 .Preventive Maintenance Program

Implement condition based maintenance schedules with machine condition monitors where production planning is concerned.

5 .Workforce Development

Introduce planned training of the 14.8% of defects caused by human errors, which includes six-sigma knowledge training.

6 .Supplier Quality Management

Reduce material defects (3.7% of total), by increasing the quality of the incoming inspection procedures.

7.3 Strategic Improvements (6-12 Months)

7 .Integrated Management System

Design collaborative optimization protocols of the decisions to pursue production, maintenance and quality control.

8 .Extended Operations Evaluation

Analyze economic sustainability of sustained production schedules using performance in October.

9 .Advanced Quality Systems

Introduce Six Sigma program implementation with a specific plan of lowering the rates of defects from 0.64% to 0.38% in 12 months.

10 .Future Research Expansion

Applicability of this study approach to other product lines (freezers, horizontal displays).

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