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Article

Reliability assessment and accelerated life testing in a metalworking plant

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ABSTRACT

Reliability assessments are useful for determining how well products, systems, and services maintain their quality over the course of time and through various conditions. In this paper, a reliability assessment of a metalworking plant was conducted, as well as accelerated life testing of the plant's spot-welded and riveted products. The overall layout of the plant was complex, requiring the use of equations to calculate the reliability of stations being connected in series and parallel in order to determine the overall reliability of the system. Furthermore, equations for mean life and failure rate were used in determining the estimate of mean life for the tested components, as well as the rate at which the components fail, respectively. The results indicated that the metalworking plant had a reliability of 0.81 or 81%. Moreover, the results indicated that the failure data of the spot-welded products follow the exponential model, with the failure rate of the products being constant throughout the period under investigation. The failure data of the riveted products follow the Weibull model, increasing throughout the period under investigation. This study presents a procedure for aiding production and maintenance managers in conducting reliability assessments of their production systems.

1. Introduction

Metalworking plants are responsible for processing metals by shaping and reshaping them to create useful items, components, assemblies, and other large-scale structures. Metalworking is responsible for the production of large structures like buildings, ships, and bridges, as well as more precise engine parts and delicate items such as jewelry. The process has evolved from the prehistoric times of shaping metals using simple hand tools to more modern and highly technical processes [1]. The modern processes include forming through bulk forming processes or sheet and tube forming processes; cutting through milling, turning, threading, grinding, or filing; and joining through riveting, brazing, soldering, or welding. All these processes need high reliability in order to produce high-quality products consistently and on time. Reliability is the probability that a product, system, or service adequately performs its required function for a specific period of time, operating in a particular environment without failure [2]. Unreliable products, systems, and services can be caused by several reasons, such as the complexity of the system due to the increasing integration of mechanical, electronic, and software parts into systems and products. The complexity of these systems makes it impossible for them to run without multiple flaws being present [3-5]. Defective products and systems can lead to direct costs, such as product recalls, warranty issues, and legal obligations, as well as indirect costs, such as market share loss and customer relationship damage [6,7]. Reliability assessments are key for maintaining system stability, improving quality, and reducing losses in health, manufacturing, agricultural, and service provision systems. These assessments help identify sources of failure and aid in failure prevention and control [8]. It can be seen that with customers increased demand for high-quality and reliable products delivered on time, reliability assessments are an indispensable tool for production companies to meet customer demand. These companies need to be faster, better, and more economical than their competitors in meeting customer demand in order to thrive. Reliability assessment can be achieved through extensive testing using several techniques such as failure mode and effect analysis, Petri nets, fuzzy logic neural networks, etc. [9-11]. In cases where wrong or oversimplified reliability models are used for assessment and making decisions, system performance can be damaged, thereby affecting safety and security [12]. Reliability assessments are useful wherever there are products, systems, or services that provide the value of a specific quality in order to determine how well these products, systems, or services perform their function [13,14]. Life testing refers to experimental tests designed to ascertain the life expectancy of structures by testing the structure at specific stress conditions similar to those of normal operation conditions.

The process is aimed at measuring one or more reliability characteristics of experimental units under consideration. Most metalworking products available today are highly reliable with high mean times to failure due to substantial improvements in science and technology. Therefore, obtaining adequate lifetime distribution data and associated parameters in a timely manner using conventional life testing experiments is difficult. As a result of this, reliability analysts have resorted to accelerated life testing, where tested items are subjected to environmental conditions far more severe than normal operating conditions [15]. This causes the tested items to fail more quickly, drastically reducing the time required for the test and the number of items that need to be tested. Product failure can be due to careless planning, substandard raw materials, wear-out, or fatigue. Products put together by various mechanical means, such as welding and riveting, are prone to failure at joints, necessitating life testing of these products [16-18]. Many systems, such as manufacturing supply chains, service providers as well as agricultural systems, need reliability assessment in order to improve productivity and meet customer needs better [19, 20]. Therefore, the aim of this research is to present a procedure for reliability assessment and product life testing, thereby aiding production and maintenance managers in implementing these concepts in their production systems. The following sections present the methods utilized as well as the results of the metalworking plant reliability assessment and accelerated life testing study.

2. Methodology

The reliability assessment was conducted in a metalworking plant that produces various sheet metal products. The metalworking plant consists of five sections: shearing sections, press shops, fabrication sections, paint shops, and assembly sections. At the shearing sections, mild steel sheets are cut into various sizes and shapes depending on the nature of the product to be manufactured. At the press shops, the processed materials from the shearing department undergo various changes in shape and dimensions through notching, bending, hole piercing, and embossment. At the fabrication sections, additional attachments are welded to processed materials from the press shop by spot welding. The materials from the press shop and fabrication department are moved to the paint shop, where they are hung on conveyors, spray painted, and dried in a special oven. In the assembly sections, all the individual parts of the products to be manufactured are fastened and assembled to create complete units by riveting. Therefore, the focus of this study is the calculation of the overall reliability of the entire metalworking plant, as well as accelerated life testing of spot welded and riveted components manufactured by the plant. This serves to gain an overall understanding of the reliability of the plant and develop expressions for predicting the failure rate and mean life of the manufactured components.

2.1 Overall reliability of the metalworking plant

The five sections of the metalworking plant consist of fourteen individual stations, which are connected in series and parallel. Therefore, the entire plant is a complex system, and the two basic equations for calculating the reliability of series and parallel systems can be combined to calculate the overall manufacturing plant reliability. The equation for calculating the reliability of a series system was obtained from Ebeling [21]:

$$R_S = \prod_{i=1}^{n} R_i \qquad (1)$$

where R_S is the reliability of the series system, and R_i is the reliability of the i_{th} component.

The equation for calculating the reliability of a parallel system was obtained from Ebeling [21]:

$$R_P = 1 - \prod_{i=1}^{n}(1 - R_i) \qquad (2)$$

where R_P is the reliability of the parallel system, and R_i is the reliability of the i_{th} component.

The procedure for evaluating the overall metalworking plant reliability is to replace the parallel sections having various individual reliabilities with an equivalent section having a single reliability, then evaluate the resulting series system, equivalent to the original system.

2.2 Nonreplacement accelerated life testing

The spot welded and riveted components were subjected to non-replacement accelerated life tests in order to develop the failure rate prediction expressions. The components were subjected to constant/static loading tests to assess how well the component would withstand a sustained load without failure. Failure, in this case, refers to the component breaking apart or separating at the joined spots. The two models investigated in the component life testing are the exponential model and the Weibull model.

2.2.1 Exponential model

The exponential model is suitable for describing the failure-time distribution of a component when the failure rate of the component is constant throughout the period under investigation. By the exponential model, the failure-time distribution of each component was obtained from Lawless [22] as:

$$f(t) = \alpha \cdot e^{-\alpha t} \qquad t > 0, \text{ where } \alpha > 0 \qquad (3)$$

where α is the constant failure rate, and t is the observed failure times.

If n components are put on test and life testing is discontinued after a fixed number of components have failed, r ($r \leq n$), and the observed failure times are $t_1 \leq t_2 \leq \cdots \leq t_r$. The mean life of the component is $\mu = \frac{1}{\alpha}$.

According to Lawless [22], the estimate of mean life can also be expressed as

$$\hat{\mu} = \frac{T_r}{r} \qquad (4)$$

where T_r is the accumulated life of the test until the r_{th} failure occurs, and r is the number of failures. The failure rate is estimated by $1/\hat{\mu}$.

Also, from Lawless [22], the accumulated life to r failures for non-replacement tests is given by:

$$T_r = \sum_{i=1}^{r} t_i + (n - r)t_r \qquad (5)$$

To investigate if failure data follows the exponential model, a total time on test plot is made by plotting the total time on test until the i_{th} failure, T_i, divided by the total time on test through the last (r_{th}) observed failure, T_r, against i/r. If the plot follows a straight line along the 45-degree line, the failure data is exponential. However, if the plot is a curve above the 45-degree line, the failure data follows an increasing hazard rate model, and the adequacy of the Weibull model can be checked.

2.2.2 Weibull model

When the failure rate of a component is not constant, but increasing and decreasing throughout a period under investigation, the Weibull model is more suitable for predicting the failure rate of such component.

According to Lawless [22], the Weibull distribution is given by:

$$f(t) = \alpha\beta t^{\beta-1}e^{-\alpha t^{\beta}} \qquad t > 0,\ \text{where } \alpha > 0,\ \beta > 0 \qquad (6)$$

where f(t) is the probability density of the Weibull distribution at time t, α is the scale parameter and β is the shape parameter.
From Johnson et al. [23], the mean of the Weibull distribution having the parameters α and β may be obtained by evaluating the integral:

$$\mu = \int_0^{\infty} t \cdot \alpha\beta t^{\beta-1}e^{-\alpha t^{\beta}}dt \qquad (7)$$

substituting $u = \alpha t^{\beta}$, we get

$$\mu = \alpha^{-1/\beta}\int_0^{\infty} u^{1/\beta}e^{-u}\,du \qquad (8)$$

The integral, $\int_0^{\infty} u^{1/\beta}e^{-u}\,du$, is the gamma function $\Gamma\left(1+\frac{1}{\beta}\right)$ evaluated at $1+\beta^{-1}$, therefore the mean time to failure for the Weibull model is:

$$\mu = \alpha^{-1/\beta}\Gamma\left(1+\frac{1}{\beta}\right) \qquad (9)$$

From Johnson et al. [23], the equation for determining the shape parameter, β is:

$$\frac{\sum_{i=1}^{r} t_i^{\beta}\ln t_i + (n-r)t_r^{\beta}\ln t_r}{\sum_{i=1}^{r} t_i^{\beta} + (n-r)t_r^{\beta}} - \frac{1}{\beta} - \frac{1}{r}\sum_{i=1}^{r}\ln t_i = 0 \qquad (10)$$

where β is the shape parameter, r is the number of failures at which the test is terminated, n is the number of components being tested, t_r is the time of the rth failure, t_i is the time of the ith failure.
Also from Johnson et al. [23], the equation for determining the scale parameter, α is:

$$\alpha = \frac{1}{\frac{1}{r}\left[\sum_{i=1}^{r} t_i^{\beta} + (n-r)t_r^{\beta}\right]} \qquad (11)$$

where β is the shape parameter, r is the number of failures at which the test is terminated, n is the number of components put on the test, t_r is the time of the rth failure, t_i is the time of the ith failure.
The α and β parameters are obtained by the maximum likelihood method. The method is implemented in Python programming language using the NumPy and SciPy libraries.
From Johnson et. al [23], the Weibull failure-rate function is given by,

$$z(t) = \alpha\beta t^{\beta-1} \qquad (12)$$

where α is the scale parameter and β is the shape parameter.
According to Johnson et. al [23], the Weibull plot is a plot of $\ln t_i$ versus Weibull score given by $\ln\ln\frac{1}{1-\widehat{F(t_i)}}$, therefore:

$$x_i = \ln\ln\frac{1}{1-\widehat{F(t_i)}} \qquad (13)$$

and

$$y_i = \ln t_i \qquad (14)$$

From Johnson et. al [23], $\widehat{F(t_i)}$ is given by

$$\widehat{F(t_i)} = \frac{i}{n+1} \qquad (15)$$

If the plotted points do not fall reasonably close to a straight line, the assumption that the underlying failure-time distribution is of the Weibull type is contradicted.

3. Results and discussion

This section presents the results of calculating the reliability of the entire metalworking plant as well as the mean life and failure rate values of the components in the non-replacement accelerated life testing study.

3.1 Calculating the reliability of the metalworking plant

The five sections of the metalworking plant consist of fourteen individual stations, which are connected in series and parallel. The shearing section consists of two shearing stations connected in parallel; the press shop section consists of three stations connected in parallel; the fabrication section consists of two stations connected in parallel; the paint shop section consists of four stations connected in parallel; and the assembly section consists of three stations connected in parallel. Therefore, the entire plant is a complex system, and the two basic equations for calculating the reliability of series and parallel systems were combined to calculate the overall manufacturing plant reliability. For resolving the parallel stations into equivalent single stations, the equation was used, while for resolving the series stations into equivalent single stations, the equation was used. Figure 1 shows the metalworking plant layout and the various reliabilities of the individual sections.
The two individual parallel shearing stations can be replaced by a single shearing section having a reliability of

$$R_{shearing} = 1 - [(1 - 0.8)(1 - 0.85)] = 0.97$$

The three individual parallel press shop stations can be replaced by a single press shop section having a reliability of

$$R_{press\ shop} = 1 - [(1-0.65)^2(1-0.7)] = 0.96$$

The two individual parallel fabrication stations can be replaced by a single fabrication section having a reliability of

$$R_{fabrication} = 1 - [(1-0.75)(1-0.7)] = 0.93$$

The four (4) individual parallel paint shop stations can be replaced by a single paint shop section having a reliability of

$$R_{paint\ shop} = 1 - [(1-0.60)^2(1-0.65)(1-0.7)] = 0.98$$

The three individual parallel assembly stations can be replaced by a single assembly section having a reliability of

$$R_{assembly} = 1 - [(1-0.75)(1-0.55)(1-0.60)] = 0.96$$

Finally, the resulting series system, equivalent to the original system, has a reliability of

$$R_{plant} = R_{shearing} \times R_{press\ shop} \times R_{fabrication} \times R_{paint\ shop} \times R_{assembly}$$

$$= 0.97 \times 0.96 \times 0.93 \times 0.98 \times 0.96 = 0.81$$

From the foregoing, the overall reliability of the metalworking plant can be improved by replacing certain stations with low reliabilities by several similar stations connected in parallel. This is because if the manufacturing plant consists of a number (n) of similar independent stations connected in parallel, the high-reliability parallel stations will make up for the low-reliability parallel stations, thereby increasing the reliability of the section. Also, the section will fail to function only if all n stations fail.

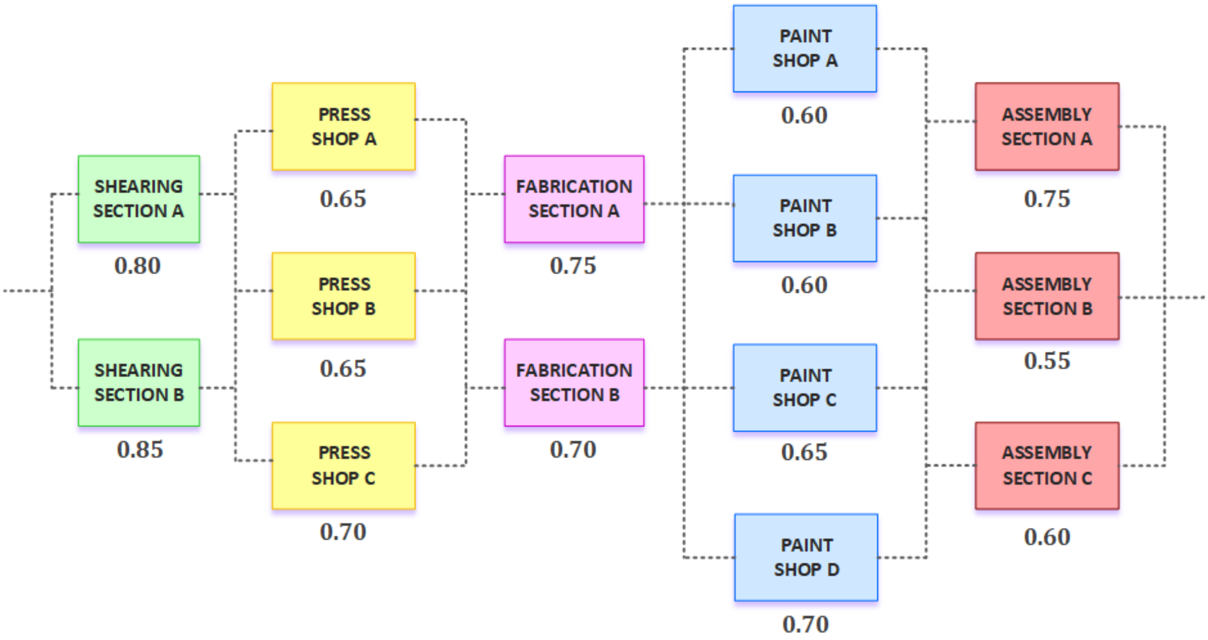

Figure 1. Metalworking plant reliability

Table 1. Data from spot-welded components life test

i	Failure times, t_i (hours)	Accumulated life, T_i (hours)	T_i/T_r	i/r	$\widehat{F(t_i)}$	y_i	x_i
1	186	11160	0.185474	0.1	0.02	5.23	-4.10
2	231	13815	0.229599	0.2	0.03	5.44	-3.40
3	501	29475	0.489862	0.3	0.05	6.22	-2.99
4	541	31755	0.527755	0.4	0.07	6.29	-2.69
5	626	36515	0.606864	0.5	0.08	6.44	-2.46
6	701	40640	0.67542	0.6	0.09	6.55	-2.27
7	771	44420	0.738242	0.7	0.11	6.65	-2.10
8	961	54490	0.905601	0.8	0.13	6.87	-1.96
9	1,031	58130	0.966096	0.9	0.15	6.94	-1.83
10	1,071	60170	1	1	0.16	6.98	-1.72

3.2 Calculating mean life and failure rate of manufactured components

During the non-replacement accelerated life test, $n_w = 60$ units of components joined by spot welding and $n_r = 60$ units of components fastened by riveting were tested, and the test was truncated after r = 10 items failed from each of the spot-welded and riveted components. Table 1 shows the results from the spot-welded components life test.

While Table 2 shows the results from the riveted components life test. Figure 2 is an exponential model plot of Scaled Time on Test (Ti/Tr) versus i/r for the spot-welded components.

From Figure 2, the plot seems to follow a straight line along the 45-degree line, therefore the failure data is exponential. From equation (4) the mean life of the spot-welded components is calculated as

$$\hat{\mu} = \frac{60{,}170}{10} = 6{,}017 \text{ hours}$$

and the failure rate of the spot-welded components is:

$$\text{Failure rate} = \frac{1}{6{,}017} = 0.00017 \text{ failures per hour}$$

This is equivalent to 0.17 failure per thousand hours.

Figure 3 is an exponential model plot of Scaled Time on Test (T_i/T_r) versus i/r for the riveted components. From Figure 3, the plot is a curve above the 45-degree line, therefore, the failure data follows an increasing hazard rate model, and the adequacy of the Weibull model needs to be checked. Figure 4 is a Weibull model plot of the riveted components data. From Figure 4, the majority of the plotted points fall reasonably close to a straight line, therefore the assumption that the underlying failure-time distribution is of the Weibull type cannot be contradicted. Therefore, the maximum likelihood estimators are computed using Python and the values are α = 405.86 and β = 2.72. Hence, from equation (9) the mean time to failure for the riveted components is:

$$\mu = (405.86)^{-1/2.72}\Gamma\left(1 + \frac{1}{2.72}\right) = 0.098 \text{ hours}$$

Also, from equation (12), the failure rate function is given by

$$Z(t) = (405.86)(2.72)t^{2.72-1} = 1103.94t^{1.72}$$

Table 2. Data from riveted components life test

i	Failure times, t_i (hours)	Accumulated life, T_i (hours)	T_i/T_r	i/r	$\widehat{F(t_i)}$	y_i	x_i
1	171	10260	0.304957793	0.1	0.02	5.14	-4.10
2	205	12266	0.364582095	0.2	0.03	5.32	-3.40
3	216	12904	0.383545357	0.3	0.05	5.38	-2.99
4	251	14899	0.442842706	0.4	0.07	5.53	-2.69
5	326	19099	0.56767923	0.5	0.08	5.79	-2.46
6	381	22124	0.65759125	0.6	0.10	5.94	-2.27
7	391	22664	0.67364166	0.7	0.11	5.97	-2.10
8	491	27964	0.831173463	0.8	0.13	6.20	-1.96
9	561	31604	0.939365117	0.9	0.15	6.33	-1.83
10	601	33644	1	1	0.16	6.40	-1.72

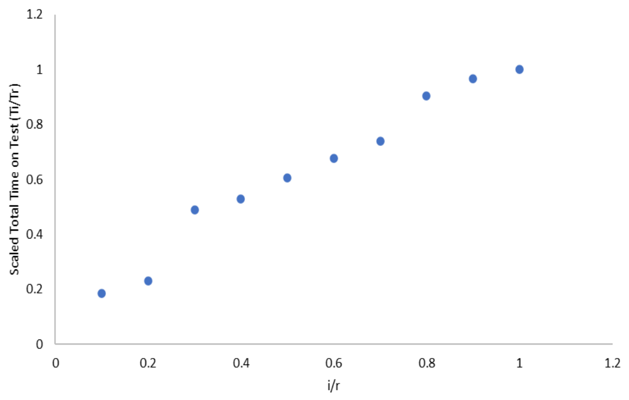

Figure 2. Exponential model plot for spot-welded components

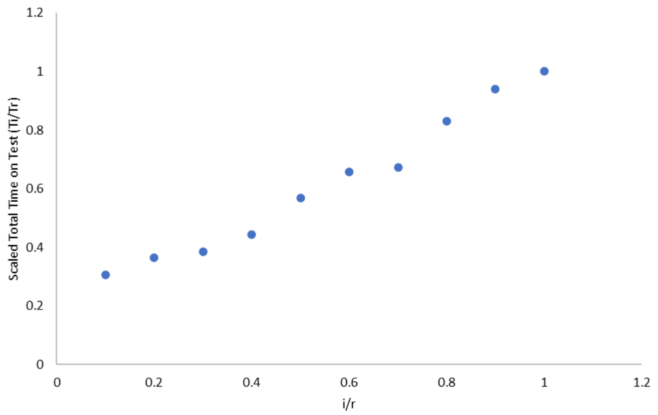

Figure 3. Exponential model plot for riveted components

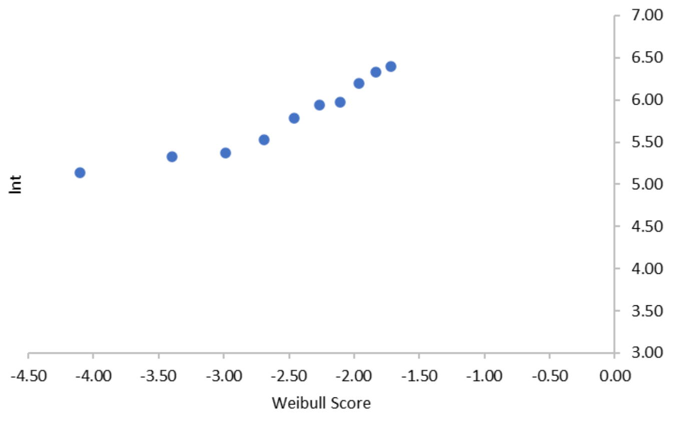

Figure 4. Weibull model plot for riveted components

4. Conclusion

Regular reliability assessments on manufacturing plants are very crucial for improving the overall productivity of the plants. Hence, production managers are usually faced with the responsibility of determining the probability that products, systems and services will carry out their functions adequately for a specific period of time without failure. Therefore, the aim of this research was to present a procedure for reliability assessment and product life testing, thereby aiding production and maintenance managers in implementing these concepts in their production systems. This study assessed the reliability of a complex metalworking plant having stations connected in series and parallel. Though, the reliability of the plant was calculated to be 0.81, the overall reliability of the metalworking plant can be improved by replacing certain stations with low reliabilities with several similar stations connected in parallel. This is because if the manufacturing plant consists of a number (n) of similar independent stations connected in parallel, the high reliability parallel stations will make up for the low reliability parallel stations, thereby increasing the reliability of the section. Also, the section will fail to function only if all n stations fail. Accelerated life testing of spot-welded and riveted components was conducted, and it was shown that the spot-welded components failure data followed the exponential model. However, the failure data of the riveted components showed an increasing hazard rate, thereby following the Weibull model. This study presents a procedure for aiding production and maintenance managers in conducting reliability assessments of their production systems.

Ethical issue

The author is aware of and complies with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The author declares no potential conflict of interest.

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