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Assessing production process reliability using statistical methods

K e y w o r d s

Production process, Pareto-Lorenz method, reliability, quality.

S ł o w a k l u c z o w e

Niezawodność, jakość, proces produkcyjny, metoda Pareto-Lorenza.

S u m m a r y

This publication presents a concept for assessing product quality from the perspective of production process reliability and taking into account operating costs. The stability of a production process can be assured by reducing its sensitivity to the impact of identified sources of variation. This can be done using statistical methods and models. The application of statistical experiments is illustrated with the example of the Pareto-Lorenz method used as a tool for product quality assurance in cold sheet rolling. The Pareto-Lorenz method is inexpensive and easy to use. The proposed approach can be used in the process of producing selected elements of complex technical structures, network systems etc.

1. Introduction

This article deals with the subject of developing and assessing the reliability of a production process from the perspective of both the quality of the product and the reliability of the technical facility. The following statistical

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procedures have been proposed for assessing the product quality: the Pareto-Lorenz analysis and the analysis of the production process capacity by means of selected indicators [10]. In the analysed case, the reliability assessment of a facility should be conducted taking into account operating costs [11]. The main criterion for assessing the production process is its stability, which requires the variations of features from the desired (nominal) values to be minimised. This means reducing the sensitivity of the process to the impact of identified sources of variations. In order to achieve this, mathematical models which provide information on the nature of the necessary adjustments should be used. The right tools here are statistical experiments and procedures. Reasons for variations should be eliminated in the production process and the operation by on-line control. The design process of production and control must include the definition of factors that can be controlled during product manufacturing or operation in such a way that, regardless of their variability, the quality deviation from the optimum can be minimised. This design method yields products that are resistant to interference or operating condition changes (e.g. changing weather, raw material availability etc.).

Contemporary production processes that are to ensure high product quality necessitate the use of systems for assessing and supervising the technical condition of equipment and superior monitoring and control [8, 9]. Keeping equipment in an acceptable technical condition requires continuous or regular monitoring of operating parameter changes which supports analysing and assessing the operating process of the plant, the possible causes of flaws in operation and their potential consequences at various complexity levels of the facility. A computer-aided system for assessing the reliability of facilities and supervising their technical condition guarantees that the required quality level of production processes will be achieved [7]. This is particularly true of complex technical facilities, such as process lines, specialised plants used in metallurgy and mining, network systems, etc.

Quality assurance functions should be implemented within a system that determines the organisational structure, the division of responsibilities, processes, and resources that support achieving quality policy objectives [1].

The need to use production technologies which are effective in terms of the quality achieved and which help to eliminate defective products and deviations from desired values in manufacturing and assembly processes is considered to be the toughest challenge faced by enterprises that want to keep up with the requirements of global competition.

To meet this challenge, the following should be defined:

- The way (method) of quality development and estimation; and,
- The method for improving and maintaining quality at the required level.

This is because the size of losses is inversely proportional to product quality [3].

Processes of modelling, controlling and assessing complex operational systems and their structures use such methods (quality tools) as the following: FMEA (Failure Mode and Effect Analysis), QFD (Quality Function Deployment), SPC (Statistical Process Control), Six Sigma, Taguchi method and Robust Design [10].

The basic principle of FMEA is the ability to foresee the risk that defects will appear in products, assess their consequences and diagnose their causes, which makes it possible to take preventive steps. The QFD method essentially consists in finding the greatest possible number of factors that may impact final product quality by improving the cooperation between different departments within the enterprise. The need to use production technologies effective in terms of the quality achieved necessitates the use of SPC as one of the methods. The statistical quality control of the production process should ensure its stability by taking into account all factors that influence its course as well as by the ability to correct undesirable changes of parameters that impact the quality and reliability.

Quality can be assessed statistically with the use of control charts, process course diagrams, histograms, stratification, scatter charts, etc.

The use of statistical procedures to assess product quality is presented on the example of a cold sheet rolling mill with the use of the Pareto-Lorenz analysis. A concept based on the Pareto-Lorenz diagram is inexpensive, easy to use and yields measurable economic effects [10].

2. Reliability as a quantitative measure of facility quality

In this analysis, the basic measure to assess product quality is the reliability of the production process assessed from the perspective of the reliability of facilities running the process.

Assuming that the reliability of a device is characterised by the suitability of elements and the operating cost C, we can assume in accordance with [11], that the average value of reliability of the device - P is determined by the following relationship:

$$P = \frac{1}{T_0}\left[\sum_{i=1}^{n}\int_{(i-1)\Theta}^{i\Theta - T_k} R(t)dt + \int_{n\Theta}^{T_0} R(t)dt\right] \tag{1}$$

where: T_0 – device operation duration;
Θ – time between device inspections;
T_k – duration of a single device inspection;
n – number of regular inspections;
$R(t)$ – reliability indicator of device`s elements.

Operating cost C can be estimated in accordance with [11] according to the following formula:

$$C = n\left(C_k + \sum_{j=1}^{N} S_j m_j\right) + C_s \tag{2}$$

where: C_k – expenditure to control the operability of all device elements during a single inspection;
S_j – expenditure to restore the j^{th} element;
m_j – the average number of defects of the j^{th} element in one interval between inspections;
C_s – expenditure for the entire operating life, independent of the facility inspection and element repair.
j € $[1;N]$ – number of elements.

The parametric relationship between operating costs and the reliability makes it possible to estimate the reliability as a function of costs under the assumption that time between failures has an exponential distribution. The model presented below makes it possible to assess the inspection and preventive maintenance duration according to the following formula [11]:

$$T_k = PT_{ks} + (1-P)T_n \tag{3}$$

where: T_{ks} – duration of the inspection of device operability;
T_n – failure repair duration.

According to the assumptions of the model, the inspection of the operability of a device consists in similar inspections of the operability of particular assemblies. This means that the condition of device is inspected using a system of activities with the structure of *S(k, m ,N / k=N, m=1).*

$$T_{ks} = \sum_{i=1}^{N} \tau_i \tag{4}$$

where: τ_i – random variable of the inspection duration of the i^{th} assembly of a device.

Knowing quantities makes it possible to forecast production and profits. Consequently, we can determine repair duration from the following relationship:

$$T_n = \sum_{i=1}^{N} Q_i T_{ni} + \sum_{i>j}^{N} Q_{ij} \left(T_{ni} + T_{nj}\right) + ... \quad (5)$$

where: Q_i – probability that the i^th^ assembly of device is inoperative;
T_{ni} – repair duration of the i^th^ element of device;
Q_i – probability that the j^th^ element of the i^th^ assembly is inoperative.

In the assessments made, it seems advisable to determine a group of reliability-operational indicators of the device [5] specified in Table 1.

Table 1 contains the following principal assessment criteria of a device: 1 – durability, 2 – correct operation, 3 – cost-effectiveness, 4 – reparability (the + sign shows that the indicator is applicable).

Table 1. Reliability-operational indicators
Tabela 1. Wskaźniki niezawodnościowo-eksploatacyjne

No.	Indicator name	Assessment criteria			
		1	*2*	*3*	*4*
1	Damage stream parameter	+	+	-	-
2	Replacement stream parameter	+	+	-	-
3	Adjustment stream parameter	+	+	-	-
4	Average cost per repair	-	-	+	-
5	Average outage duration per repair	-	-	-	+
6	Total failures	+	+	+	-
7	Total repair cost	-	+	-	-
8	Duration of outages in inoperable condition	+	+	-	-

The cost-effectiveness is assessed using average values of repair costs [11]. The basic indicator for assessing the reparability is the average time to repair a failure. The duration of an outage in an inoperable condition, frequently due to the shortage of spare parts, should also be included.

To analyse and assess the operating quality from the perspective of reliability and taking into account operating costs with the use of the proposed indicators, the operational tests have to be conducted in accordance with the procedure proposed in [4].

3. Pareto-Lorenz analysis as a tool for product quality assurance in cold sheet rolling

The proposed quality assurance tool is the Pareto-Lorenz diagram and the Pareto principle. The Pareto graph is based on the principle that often only a few factors influence the majority of effects. The application of the Pareto graph helps to determine which recorded defects of the sheets produced should be eliminated first to obtain an improvement in the quality condition of the products.

The Pareto-Lorenz diagram is mainly aimed at streamlining analyses of data collected during product inspection, processing this data and presenting the results in a graphic form.

The diagram should also show the direction of repairs which will yield the maximum effect and those that should be omitted, those that should not be needlessly focused on, and the causes which have no significant impact on a non-compliance that occurs, whose elimination will, therefore, have no significant impact on the total number of failures [2].

The greatest improvement is obtained with the least effort by separating the most important factors from the less important ones. The synonyms for the Pareto method are as follows: Lorenz curves, Pareto-Lorenz analysis, the 80-20 rule, ABC method [10].

The Pareto analysis is suitable for organising and analysing previously collected data. It is used when the goal is to prevent negative phenomena that occur most frequently and phenomena that cause the greatest cost. The research was conducted using the example of a cold sheet rolling mill. The range of products of the facility is presented in Table 2 [12], and the course of the technological process of rolling is presented in Fig. 1.

Table 2. Types of sheet produced
Tabela 2. Rodzaje produkowanych blach

PRODUCT	**Thickness**	**Width**	**Sheet length**	**Coil/packet weight**
	[mm]	**[mm]**	**[mm]**	**[t]**
Black plate in coils	0.18-2.50	700-1550	-	max. 15
Black plate in sheets	0.18-2.50	700-1550	**440-4000**	**1.0-5.0**
Hot-galvanized sheet in coils	0.40-2.50	700-1250	-	up to 7.0
Hot-galvanized sheet in sheets	0.40-2.50	700-1250	965-4500	2.0-5.0
Electro-galvanised sheet in coils	0.50-1.50	700-1550	-	up to 25
Electro-galvanized sheet in sheets	0.50-1.50	700-1550	1400-3000	3.0
Strips cut lengthwise from the above sheet	0.50-2.50	25-680	-	0.04-3.0

Quality requirements will be met by implementing a documented quality system. The system should be revised when the methods of service provision to customers are improved. In addition, all irregularities detected in the operation of the quality system which show that changes are needed must be discussed and consulted at management meetings to review the quality system.

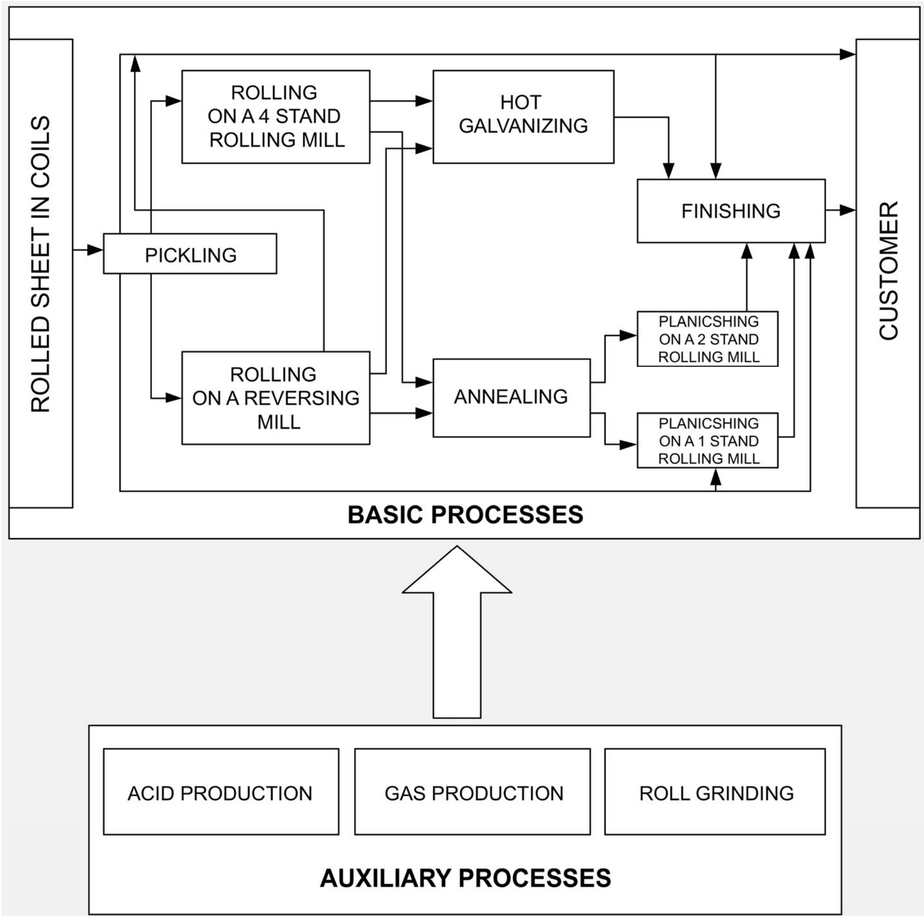

Fig.1. The cold sheet rolling process
Rys. 1. Proces walcowania blach na zimno

The statistical methods that are selected and developed should also be used in the cold rolling process in accordance with a defined, documented procedure for determining, supervising and verifying the process capacity and product characteristics. These methods include the comparative analysis, the process capacity analysis, and control charts.

A decision was taken to analyse sheet metal defects. 13 types of defects that can occur were distinguished, and it was assumed that they would be measured by the number of occurrences of a given defect between January 2005 and March 2006. These defects were as follows: defects arising during the pickling, incorrect sheet sizes, corrugation, wrinkles, soiling, rolling defects, tarnishing, corrosion, mechanical damage and others.

Non-compliance occurrences found during the sheet production process were analysed using sheet production data for 2005 and the first quarter of 2006.

Defects were ranked according to the degree of their impact, where the percentage of defects and the relative cumulative percentage were calculated.

The data processed to make the quantitative analysis of detected defects is presented in Table 3.

Table 3. List of rolled sheet defects during the research period
Tabela 3. Zestawienie wad walcowanych blach w okresie badawczym

Defect type	**Percentage [%]**	**Cumulative percentage [%]**
Dimensions	19.84	19.84
Pits	15.44	35.28
Rolling defects	10.9	52.52
Corrugation	10.42	61.06
Pickling defects	10	67
Scab shell	9.68	68.1
Wrinkles	9.22	83.98
Mechanical damage	6.28	91.78
Corrosion	3.02	95.56
Soiling	2.25	97.74
Tarnishing	2.06	98.19
Other internal	0.6	99.71
Other external	0.28	100

Then a diagram was drawn on which the Pareto curve was plotted as bars (relative number) and the Lorenz curve as a curved line (relative cumulative number) – see Fig. 2.

The completed Pareto-Lorenz analysis shows that non-compliant size was the defect most frequent during the research period.

It was followed by pits, then rolling defects, corrugation, pickling defects, the scab shell and wrinkles (area A - main defects). The seven listed types of defects altogether were responsible for over 805 of all rejects detected during the analysed period. Size non-compliance of sheets was mainly due to the incorrect maintenance and the excessive wear on rollers. Eliminating the main defects first allowed the quality of sheet produced to be improved. Activities to remedy the most frequent defects should primarily be aimed at improving the supervision of sheet rolling, raise the precision of roller setting, and the regular grinding of rollers.

Afterwards, action should be taken to address defects caused by mechanical damage, corrosion and soiling (area B), which caused 15% of all rejects in the analysed period.

Sheet defects from area B can be prevented by more frequently regenerating the sliding plate which guides the strip, reducing the humidity in the bay and cutting the coil storage duration.

Defects grouped within area C (tarnishing, other internal, other external) can be omitted, since eliminating main causes generally also leads to many less important causes being eradicated, even though the links between them are not always perceived.

After completing the proposed remedial measures and waiting a specified time (e.g. one year), after which the effects of the changes made can be expected to materialise, the problem should be analysed again using the Pareto-Lorenz method.

It is apparent that the assessment concept based on the Pareto-Lorenz diagram is inexpensive and easy to apply. It allows the proportion of defective products to be cut and hence contributes to improving the quality management system.

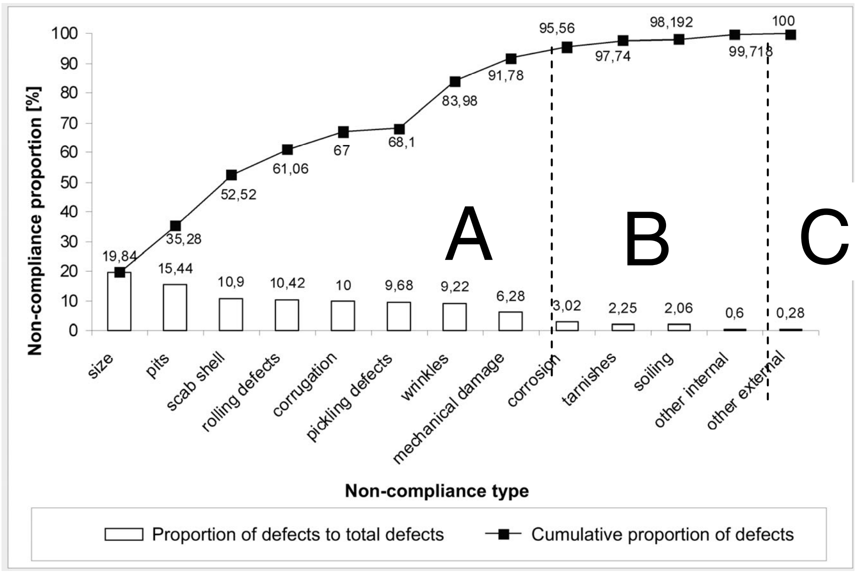

Fig. 2. Pareto-Lorenz graph for the research period
Rys. 2. Wykres Pareto-Lorenza dla okresu badawczego

4. Analysis of the production process capacity

If the goods produced do not comply with quality requirements, the production process capacity should also be assessed using the indicators proposed below.

The fundamental assumption when assessing the capacity of a process is that every process has a certain natural level of variability [10]. This is due to factors that the operator cannot influence and those that he/she does not control, because this is difficult or excessively expensive. Apart from the natural variability, there are also extraordinary deviations from the standard due to certain specific causes. These causes should also be found and eliminated so as to achieve a condition where the process is statistically regulated (stabilised).

Control charts used in statistical process control procedures can only detect extraordinary failures of the process adjustment. Process capacity assessment methods allow for determining the natural variability level that constitutes the basis for rolling out quality improvement activities. For every technological process, its basic parameters are the size tolerances - upper (U) and lower (L). If a decisive majority of elements produced are between these limits, this can be called the right quality level. The natural limits of the process are limits between which almost 100% of products manufactured should be found. In the case of the normal distribution, we talk of a 3-sigma range, which contains 99.73% of the products manufactured. The following indicator is adopted as the measure of process capacity C_p:

$$C_p = \frac{U - L}{P_{99.865} - P_{0.135}} \tag{6}$$

The upper natural process limit is $P_{99.865}$, and the lower is $P_{0.135}$.

In the case of the normal distribution, the formula will take the following form:

$$C_p = \frac{U - L}{6s} \tag{7}$$

where:

s – total standard deviation.

The upper natural process limit is $P_{99.865}$, and the lower is $P_{0.135}$.

This indicator does not take into account the natural situation of the variability range within the tolerance limits, so it may be used only to assess uniform and highly stabilised processes. To eliminate this inconvenience, the C_{p_k} indicator has to be introduced.

$$C_{p_k} = \min\left(C_{pku}, C_{pkl}\right) \tag{8}$$

where:

$$C_{pku} = \frac{U - P_{50}}{P_{99.865} - P_{0.135}} \tag{9}$$

$$C_{pkl} = \frac{P_{50} - L}{P_{99.865} - P_{0.135}} \tag{10}$$

P_{50} is the 0.5 order quartile in the distribution of the researched value, i.e. the median of that distribution.

For the normal distribution, the above formulas take the following form:

$$C_{pku} = \frac{U - \mu}{3\sigma_t} \tag{11}$$

$$C_{pkl} = \frac{\mu - L}{3\sigma_t} \tag{12}$$

where σ_t is the standard deviation whose determination takes into account all process variability types, μ - expected value.

The σ_t parameter can be estimated using an estimator based on a collective sample.

$$\sigma_t = s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{13}$$

where: s – total standard deviation;
x_i – realization of random variable;
x – average value of testing parameters;
n – sample size.

If data is available on the scattering of results for particular samples, it is also possible to use it to assess the standard deviation in accordance with the following formula:

$$\hat{\sigma} = \frac{\overline{R}}{d_2} \tag{14}$$

where $\overline{R}$ is the average range from the samples, and d_2 is a parameter dependent on the sample size.

The sample used to determine the capacity should be representative (n > 100). If the process has not been stabilised, measurements must be taken at various intervals.

5. Summary

This article addresses the subject of improving and assessing the reliability of a production process from the perspective of both the product quality and the reliability of the technical facility. The following statistical procedures have been proposed for assessing product quality: the Pareto-Lorenz analysis and the analysis of the production process capacity by means of indicators presented in Section 4. The concept for assessing the reliability of the production process using a model accounting for the operating cost and statistical experiments for assessing product quality represent a comprehensive approach to the problem of developing quality requirements. In the process analysed, an important role is played by the operator and the future user of the manufactured products.

Quality assessment using the Pareto-Lorenz method is inexpensive and easy to apply. It allows the proportion of defective products to be cut and consequently contributes to improving the quality management system. In the analysed case, a computer-aided system for assessing the reliability and supervising the technical condition of facilities should guarantee the correct course of the production process and achieving the required quality of products. These considerations were illustrated with the example of process and product quality assessment based on data about cold rolled sheets.

The presented diagram supports the claim that activities to remedy the most frequent defects should first improve the precision of roll setting, their regular grinding and improving the supervision of the rolling process.

The low cost of the proposed methodology and its universality make it suitable for application in may industrial sectors to assess the quality of selected elements of complex technical facilities, such as process lines, network systems, etc.

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Ocena niezawodności procesu produkcyjnego z wykorzystaniem metod statystycznych

S t r e s z c z e n i e

W opracowaniu przedstawiono koncepcję oceny jakości wyrobu z punktu widzenia niezawodności procesu produkcyjnego z uwzględnieniem kosztów eksploatacji. Zapewnienie stabilności procesu produkcyjnego jest możliwe poprzez zmniejszenie wrażliwości procesu na działanie zidentyfikowanych źródeł zmienności. Może ono być realizowane poprzez zastosowanie metod i modeli statystycznych. Zastosowanie eksperymentów statystycznych przedstawiono na przykładzie metody Pareto-Lorenza. Rozważania poparto przykładem oceny jakości procesu i produktu w oparciu o dane dotyczące blach walcowanych na zimno.

Koncepcja oceny niezawodności procesu produkcyjnego z wykorzystaniem modelu uwzględniającego koszty eksploatacji oraz zastosowaniem eksperymentów statystycznych w ocenie jakości wyrobów stanowią kompleksowe podejście do problemu kształtowania wymagań jakości. Niskie koszty zaproponowanej metodyki oraz uniwersalny charakter sprawiają, że może ona znaleźć zastosowanie w wielu gałęziach przemysłu w ocenie poziomu jakości wybranych elementów złożonych obiektów technicznych jak np. linie technologiczne, układy sieciowe itp.