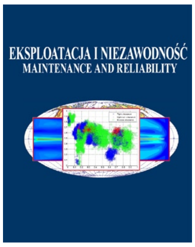

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Assessment of the modernized production system through selected TPM method indicators

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Highlights

- Modernization of a continuous production system.
- Proposed system evaluation methodology after the modernization.
- Evaluation criteria: selected TPM indices and MTBF and MTTR of production lines.
- Exemplification of the methodology for the zinc concentrate production system.

Abstract

The subject of the studies is the evaluation of the operation of a production system after modernization. The analysed case concerns the modernization forced by the end of the product lifetime. The proposed methodology is that of a multicriterial evaluation of the system operation after modernization. The evaluation criteria are selected TPM indices: availability of machinery and equipment, production process capacity, product quality and overall equipment effectiveness (OEE). The additional criteria are reliability indices MTBF and MTTR of studied production lines and the MTTR of the most unreliable equipment in each analysed line. A yearly monitoring of production process was proposed for obtaining the statistical credibility of the evaluation results. Additionally, a fuzzy indicator of acceptability of the modernization assessment was proposed. The paper presents the results of studies of the system for production of zinc concentrate from post-production waste. The obtained values of OEE, MTBF and MTTR indicators for the three tested lines make it possible to state that the modernization carried out is acceptable.

Keywords

continuous production system, system modernization, post-modernization evaluation, evaluation indices (OEE, MTTR, MTBF), process monitoring.

1. Introduction

Maintaining the continuous flow of materials and information is one of the most important tasks in production systems [3]. The main reasons for undesirable interruptions in systems operation are disruptions in supply of components and materials to relevant stations and downtime and failures of equipment in production lines. Numerous strategies and methods suggested by lean manufacturing and the operation and reliability theory are used to minimize such disruptions. The common assumption of the lean manufacturing-related methods is to ensure, maintain and improve the continuous flow of material in the production system [26, 27].

One of the methods to achieve this goal is to ensure the continuous operation of machines which is the main task of TPM (Total Productive Maintenance) [12, 13, 27]. Most publications on lean manufacturing include descriptions of various methods and options to improve the efficiency and productivity of production systems [1, 7, 15, 20]. The attempts to combine the lean manufacturing and the TMP into one consistent strategy of lean maintenance are increasingly often made [13, 22, 23]. An interesting review of literature on lean manufacturing can be found in [24, 25].

The analyses indicate that the lean monitoring level moves from the process evaluation to the company level. Conclusions presented in [29, 30] are even more far-reaching as the authors claim that the scope of lean evaluation has expended from the production process level to the supply chain level. Other methods are also suggested for a more detailed evaluation of the impact of the lean criteria on the leanness of processes, such as ANP (Analytic Network Process) [33], artificial intelligence methods [2], hybrid methods [34], and machine learning methods [4].

Another approach to improve the systems operation is Reconfigurable Manufacturing System (RMS). The principles of designing and the review of the RMS are presented in [14]. The selection of the production process in terms of maintaining the availability of the machines in the system is presented in [9]. Interested results of studies in Portuguese industrial production companies on the reconfigurability in are presented in [19].

Very significant is also the area of research on the improvement of the continuity of manufacturing processes by using the solutions from the operation and reliability theory. A systemic approach to the issues of prevention and predictable is presented in the extensive paper [36]. The states of production equipment capacity and states of quality of

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manufactured products are important indices of the operational system evaluation, so the predictive strategy for multistate systems is very interesting [10]. The chain QR oriented to quality Q and reliability R is formulated in the strategy. An interesting paper [6] presents an integrated problem of choosing the production lot size, quality control and state-based maintenance for an imperfect production system which is subject to the reliability degradation [32]. The paper [32] includes a review of multicriteria models for solving the maintenance optimization problems. The review has identified 259 publication from the MCO (Multi Criteria Optimization) area and more than 100 universally used criteria.

An innovative predictive strategy for repairable complex systems is presented in [32]. The proposed long-term strategy includes the choice of degradation features and modules of the forecasting degradation models which allow obtaining accurate failure forecasts. Original solutions for the optimization process with redundancy with limitations with the use of an innovative algorithmic approach are presented in [11, 17]. Other analyses related to modelling and optimization of m-out-of-n backup systems are included [16, 18, 28].

There are a few papers on the evaluation of modernized systems. The issues of production process modernization in Russian industrial companies are presented in [35]. The conclusion presents a model of interrelation between the production modernization and the sustainable growth of a company. Finding the optimal design by a multicriterial evaluation is described in [31]. The evaluation uses a new measure of operational complexity of individual machines based on the number of parts, machines and operations [21]. Alternative design solutions are compared with each other using selected capacity criteria, followed by a multicriterial decision-making analysis based on the Analytic Hierarchy Process (AHP).

The review indicates only very few publications related to the use of TPM in evaluation of production systems after modernization. The TPM method is most often used to improve the efficiency of the operating systems. A novelty of the proposed is taking into account the evaluation method at the stage of making the decision to modernize. This is not an evaluation of the system modernization design, but an evaluation of the operation of the modernized system after a specific, longer time of operation (e.g. a year).

2. Model of a generalized production system

The generalized production system GPS is a certain ordered set of elements A and relations R between them:

$$\mathbf{GPS} = \left\langle \{\mathbf{X},\mathbf{Y},\mathbf{T}\},\mathbf{R} \right\rangle,$$
$$\mathbf{T} : \mathbf{X} \rightarrow \mathbf{Y}.$$

where:

$X = \{X_1, X_2, \ldots X_i, \ldots X_M\}$; for $i = 1,\ldots M$ – set of external magnitudes describing input elements,

$Y = \{Y_1, Y_2, \ldots Y_j, \ldots Y_N\}$; for $j = 1,\ldots N$ – set of external magnitudes describing output elements,

$T = \{T_1, T_2, \ldots T_k, \ldots T_S\}$; for $k = 1,\ldots S$ – set of magnitudes describing the transformation of input vector into output vector,

$R = R_X \times R_Y \times R_T$ – material and information conjugations between the USP system elements and between the elements and the environment (most often close environment).

The diagram of the generalized production system is shown in Figure 1. Each system and system products have a specific, finite life, the so-called lifecycle. The continuous monitoring of selected features and system properties (acc. to Fig. 1) allows making the right decision at the right time – that is before the fourth lifecycle phase (decline of performance). In order to avoid the decision to decommission the system it is necessary to prepare the system modernization in advance (of course if it is possible and reasonable).

The reasons to make a decision to modernize the production system are usually:

- unsatisfactory economic indices,
- desire to modernize machine park,
- system adaptation to the requirements of Industry 4.0,
- approaching the fourth lifecycle phase (decline),
- limitation of availability for necessary raw materials and components,
- adaptation to changing environment requirements (e.g. EU directives), for instance in terms of environmental protection.

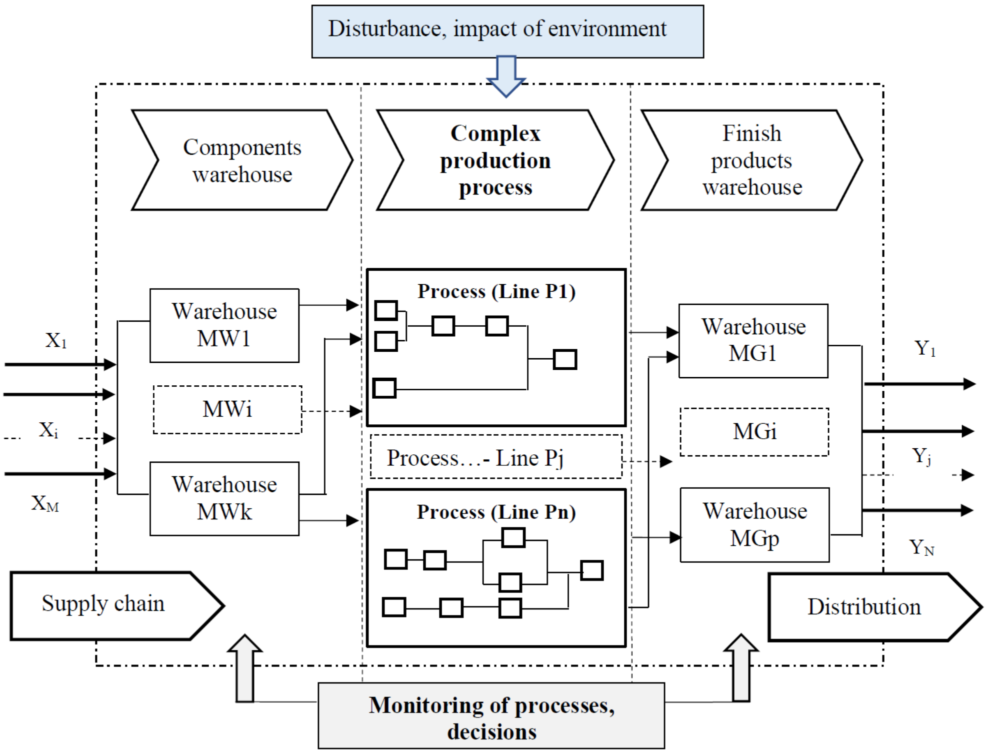

Fig. 1. Diagram of a generalized production systems GPS (own study)

The values determining thee specific character of the studied system include:

- continuous production (24 hours a day all year long),
- adaptation to changing environment protection requirements (e.g. EU directives),
- very significant limitation of supplies caused by exhaustion of current resources necessary for the production process,
- change of suppliers and components for production (an effect of the previous limitation).

The aforementioned reasons became an origin of the method for the evaluation of the production system modernization. The evaluation criteria are selected indices known from the TPM (Total Productive Maintenance).

Hence, the magnitudes describing the system outputs (acc. to Fig. 1) should include information typical to the evaluation of production systems (KPI – Key Performance Indicators) – about the process costs, achieved capacity, profitability, and also additional information on:

- availability of machines and equipment of production lines;
- product quality;
- mean time between failures;
- mean time to repair.

3. System modernization evaluation method

It was decided to modernize the system in a few stages:

Stage I – decision to modernize,

Stage II – system modernization (implementation),

Stage III – evaluation of production system after modernization.

Stage I should include a detailed identification of reasons for modernization. The identification result is the basis for three main tasks of the stage:

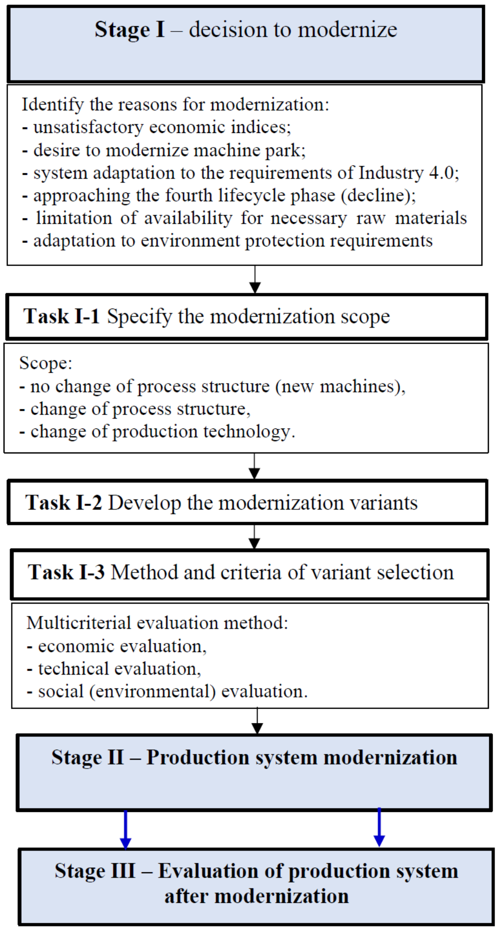

Fig. 2. Diagram of variant selection algorithm (own study)

- determine the scope of modernization;
- develop the variants of modernization;
- specify the criteria and method of selecting the variant.

A simplified variant selection algorithm is presented in Figure 2.

After the production system modernization (Stage II), it is necessary to evaluate the system operation.

The most important tasks in Stage III include:

- choose the post-modernization system evaluation criteria,
- monitor the process and collect the data about the process (over a longer time),
- process the data statistically,
- calculate the indices chosen for evaluation,
- analyse the results and make relevant decisions on further operation of the production line.

The post-modernization system evaluation algorithm is presented in Figure 3.

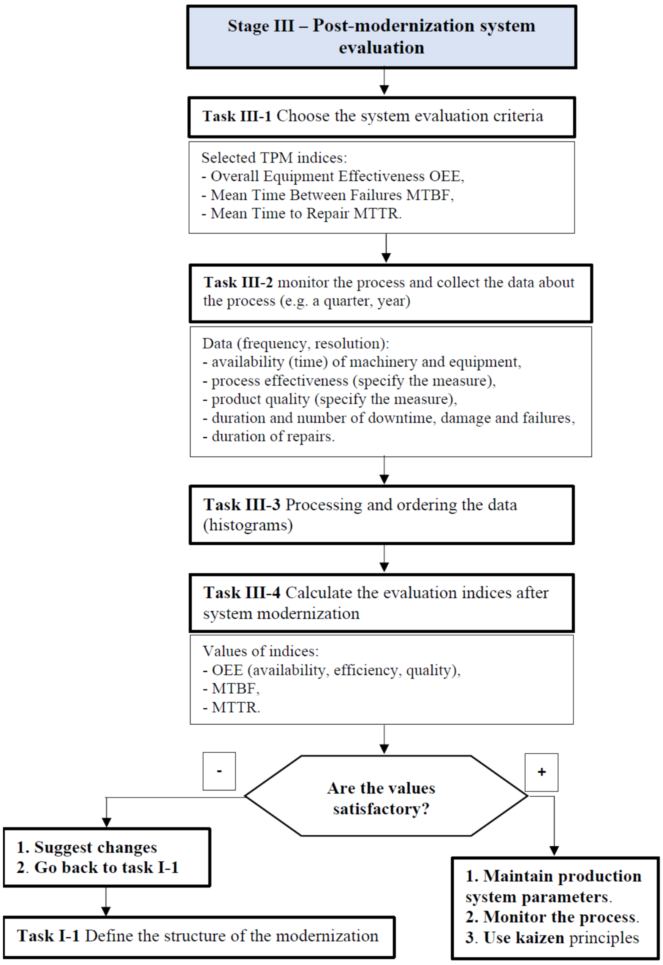

Fig. 3. Post-modernization system evaluation algorithm (own study)

In terms of chosen evaluation criteria, the following conditions should be satisfied:

- overall equipment effectiveness OEE of the studies line PLi

$$OEE_{PLi} \geq OEE_{min} \left(eg. 0,80\right),$$

- availability of machines

$$A_{PLi} \geq A_{min} \left(eg. 0,90\right),$$

- process efficiency index

$$P_{PLi} \geq P_{min} \left(eg. 0,90\right),$$

- product quality index

$$Q_{PLi} \geq Q_{min}\ (\text{eg.}0{,}95),$$

- mean time between failures

$$MTBF_{PLi} \geq MTBF_{min}\ (\text{eg. TP hours}),$$

- mean time to repair

$$MTTR_{PLi} \leq MTTR_{max}\ (\text{eg. TN hours}).$$

An important problem in this evaluation approach is a correct and accurate choice of limit, acceptable indices. Such choice can be based on the experience of engineering staff, expert knowledge, benchmarking, and also the knowledge of specificity of technological processes. Hence, the determination of an unambiguous final evaluation of the system after modernization is a complex problem. For example, in production process involving the use of post-production waste it is difficult to achieve the high product quality. For the purposes of the systems considered in the work, a simple fuzzy minimalist rule was proposed:

if

$$\bigwedge_{PLi} i = 1,..n$$

$$OEE_{PLi} \geq OEE_{min}\ \wedge\ MTBF_{PLi} \geq MTBF_{min}\ \wedge$$

$$MTTR_{PLi} \leq MTTR_{max}\ \rightarrow \text{ACCEPTABLE ASSESSMENT}$$

In order to more accurately assess the operation of the system after the modernization, it is necessary to expand the proposed methodology using the principles of expert - fuzzy assessment.

4. Exemplification – zinc production from waste

4.1. System identification

The analysed company produces zinc concentrate necessary to make raw zinc. A rapid exhaustion of calamine resources forced a change of the processing technology in order to use another batch material. A decision has been made (Fig. 2) to make the zinc concentrate from zinciferous waste, particularly from dust from electric steel-melting shops and sludge from zinc electrolysis and industrial wastewater treatment plants. In order to prevent the contamination of the environment, such waste is subjected to zinc recovery during the pyrometallurgical processing in rolldown furnaces. This method is used all over the world.

The main problems linked to the system modernization included:

1. Ensuring continuous supply of new raw material (waste) which required a mechanism stimulating the feeding the system with waste generated by many suppliers.
2. Adaptation of the new technology to new environmental protection regulations, particularly new strict European regulations on allowed sulphur oxide emissions (IPPC Directive). The production from hazardous waste requires an Integrated Permit (PRTR - *Pollutant release and transfer registers* and EPER - European Pollutant Emission Register).
3. Achieving the process efficiency indices on European level.

As a result of modernization some lines were decommissioned, and the remaining lines received additional, new equipment. Three production line were modernized PL1, PL2 and PL3, which were analysed in detail.

The production process diagram is presented in Figure 4.

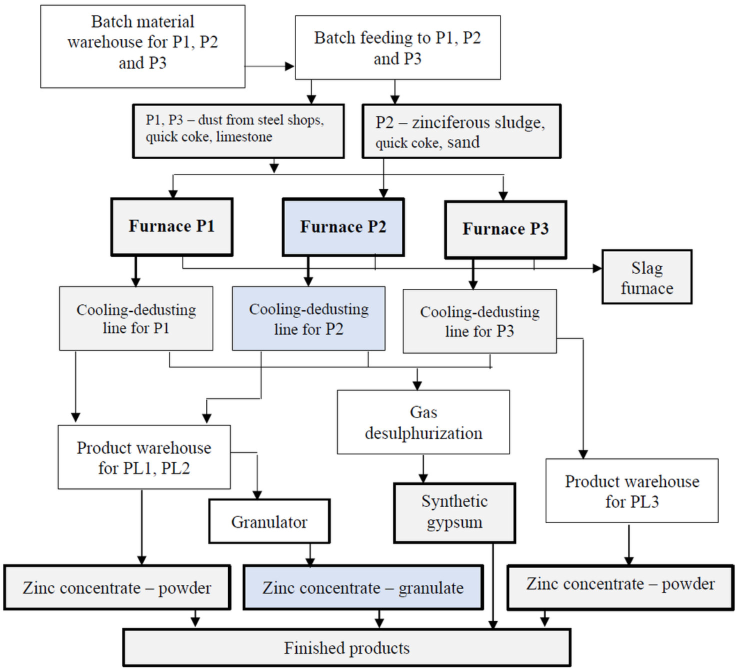

Fig. 4. Diagram of zinciferous waste processing line – after modernization (own study)

The assumption during the planning of modernization was that the production process efficiency will increase. Three basic characteristics were used to determine the efficiency of utilization of resources after modernization:

- OEE - Overall Equipment Effectiveness,
- MTTR - Mean Time to Repair,
- MTBF - Mean Time Between Failures.

In accordance with the algorithm proposed during the modernization phase, a yearly monitoring of selected parameters was recommended (Fig. 3).

The data obtained for one year of operation were the basis of a detailed statistical analysis of:

- time between failures of individual lines and furnaces,
- time of failures, damage and micro-downtime of lines and the line equipment.

Histograms were made for three lines to show the system downtimes, with indication of the reasons (planned downtime/ failure). Examples of histograms for lines PL1 and PL2 are presented in figures 5 and 6.

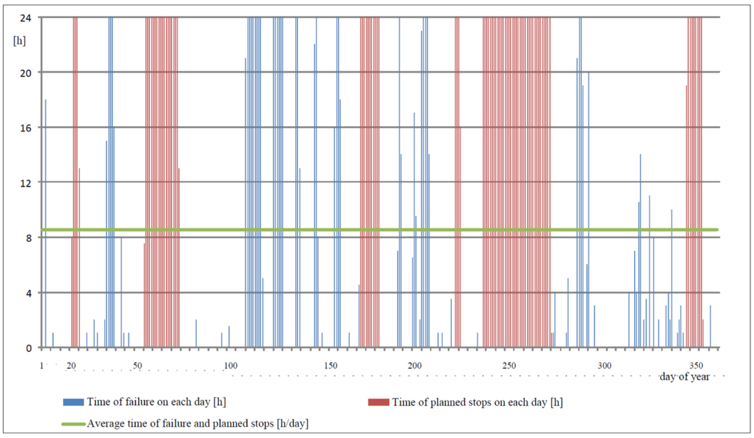

Fig. 5. Histogram of failures and planned downtime during one year for line PL1 (own study)

Figure7 presents the percent shares of times between failures, failures and planned downtime for line PL3.

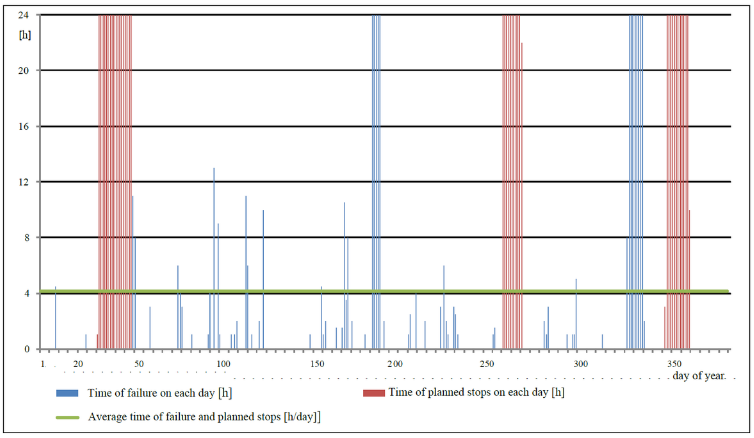

Fig. 6. Histogram of failures and planned downtime during one year for line PL2 (own study)

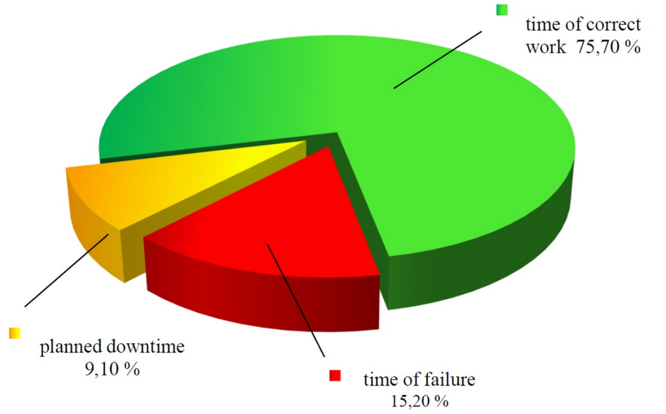

Fig. 7. Availability of line PL3 in percent (own study)

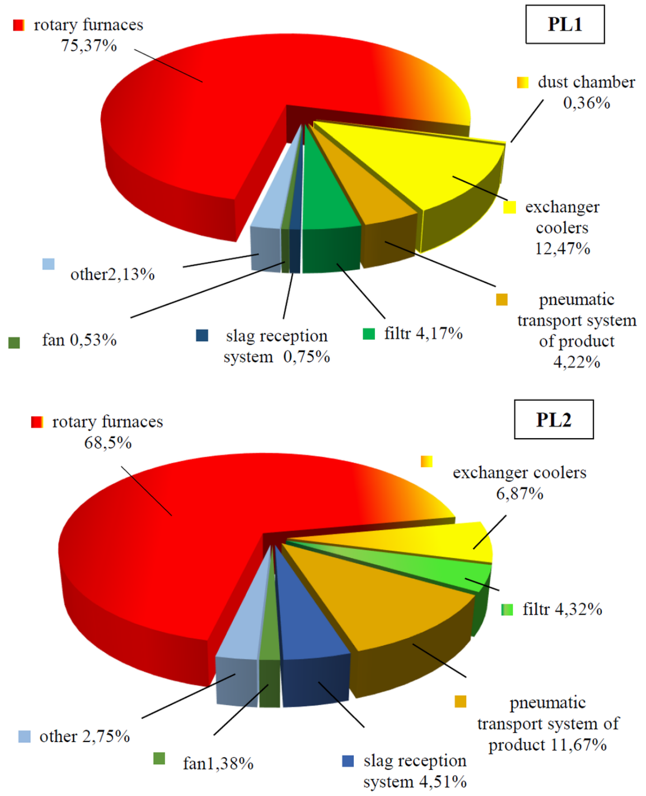

Fig. 8. Percent shares of failures individual equipment in lines PL1 and PL2 (own study)

Due to the variety of failures of machinery and equipment in the process line, the downtimes were divided to the main subgroups:

- slag reception systems,
- furnaces,
- dust chambers,
- heat exchanger coolers,
- filters,
- pneumatic product transport systems,
- fans.

Typical results for line PL1 are presented in Table 1.

The percent shares of failures of individual equipment in lines PL1 and PL2 are shown in Figure 8.

Table 1. Failure times for line PL1 by type

Failure	time [h]	number
Slag reception system		
removing lumps from rails	1	1
slag trap failure	7,5	3
Furnace		
damping	190	11
slagging	482	11
heating	159,5	11
welding works on furnace end	8	1
problems with start-up –soft-start replacement	2	1
taring the mixture scale	7,5	4
Total:	849	39
Dust chamber		
blocked screw feed under the chamber	4	1
Heat exchanger coolers		
screw feeder failure	22	2
overhaul of screw under the hot cooler	67	3
cleaning of space between exchangers	51,5	9
Filter		
high filter resistance – cleaning	44	5
filter check	2	1
failure od filter regeneration compressor	1	1
Pneumatic product transport system		
oxide pump failure	6	3
failure of line-plate feeder	41,5	10
Fan		
main fan cleaning	1	1
no compressed air	5	1
Other		
no batch	19	2
defreezing of air for batch	1	1
no power on cooling-dedusting line 1	2	1
failures of accompanying equipment	2	2
Total events	1126,5	86

4.2. Analysis of results

The OEE index was determined in order to find the efficiency of use of resources using formulas (1), (2) and (3). The index defines the percent of theoretically achievable efficiency of line or equipment:

$$OEE = A \cdot P \cdot Q \cdot 100\left[\%\right] \qquad (1)$$

where:

A – production line availability, A ∈ (0, 1),

P – process efficiency (performance), $P \in (0, 1)$,
Q – product quality, $Q \in (0, 1)$.

Calculation of process availability index A

$$A_{PLi} = \frac{A_{i2}}{A_{i1}} \cdot 100 [\%] \qquad (2)$$

$$A_{i1} = 365 \text{ days} \cdot 24 \text{ hours} - t_{ppi}$$

$$A_{i2} = 365 \text{ days} \cdot 24 \text{ hours} - t_{pp1} - t_{aw1}$$

where:

A_{i1} [h] – planned work time (available time – planned downtime),
A_{i2} [h] – operational time (planned work time – total downtime and failure time),
i – number of production line for which the index is calculated,
t_{ppi} [h] – planned downtime of the ith production line,
t_{awi} [h] – total failure time of the ith production line.

Determination of process efficiency index P

Two different approaches can be suggested for determination of the efficiency index [9].

On one hand, it can be assumed that if the furnace runs at the design capacity, and during the modernization all equipment and machines in the process line were designed for maximum design capacity of the rolldown furnace, the efficiency index for the whole process line can be taken as $P_{PLi} = 100$ %.

On the other hand, due to the complexity of the process, difficulties in maintaining the technological discipline and varying quality of batch materials, it is difficult to think that the capacity will always be kept at the highest level. It can be reduced, for instance, by growing deposits inside the furnaces. Due to the continuous character of the process, it is difficult to indicate accurate values of the efficiency index at a given time. Based on experience, it is however possible to assume that the reduction on the average should not exceed 5%. Such being the case, it is taken that $P_{PLi} = 95\%$.

Calculation of quality index Q

The quality index was determined by comparing the amount of batch material with the amount of concentrate received from it in relation to the zinc content in them, using the formula (3).

$$Q_{PLi} = \frac{Q_{i2}}{Q_{i1}} \cdot 100 [\%] \qquad (3)$$

where:

Q_{i1} [Mg] – mass content of Zn in batch,
Q_{i2} [Mg] – mass content of Zn in product.

The data from the year of production process monitoring in lines PL1, PL2 and PL3 are presented in Table 2.

The data on the mass zinc content in the batch material (dust from electric steel-melting shops and zinciferous sludge from zinc electrolysis) are presented in Table 3.

The calculations yielded the indices of availability, efficiency and quality. The results are presented in Table 4.

MTBF and MTTF

MTBF is the mean time between two failures or downtimes. The $MTBF_i$ was calculated according to the following formula:

Table 2. Results of monitoring for production lines

	Production line PL1	**Production line PL2**	**Production line PL3**
Available time [h/year]	8760	8760	8760
Planned downtime [h/year]	1999,5	996	797
Failure time [h/year]	1126,5	509,5	1331,5
Furnace failure time [h/year]	849	349	994,5
Time between failures [h/year]	5634	7254,5	6631,5

Table 3. Zinc concent in batch material and final product

Production line		weight [Mg]	Zn content [%]	Zn amount [Mg]
Line **PL1**	Batch	54 518,385	27,52	15 003,46
	Production	22 360,037	59,44	13 290,81
Line **PL2**	Batch	58 839,159	17,52	10 308,62
	Production	19 039,309	45,55	8 672,41
Line **PL3**	Batch	54 518,385	27,52	15 003,46
	Production	22 360,037	59,44	13 290,81

Table 4. Partial indices for individual lines

Index	**Production line PL1**	**Production line PL2**	**Production line PL3**
A_{i1} [h/year] A_{i2} [h/year]	6760,5 5634,0	7764,0 7254,5	7963,0 6631,5
Availability – A_{PLi}	0,833	0,934	0,833
Performance - P_{PLi}	0,95	0,95	0,95
Q_{i1} [h/year] Q_{i2} [h/year]	15 003,46 13 290,81	10 308,62 8 672,41	15 003,46 13 290,81
Quality – Q_{PLi}	0,886	0,841	0,886

$$\mathrm{MTBF}_i = \frac{t_{ppri}}{n_{ppi}}$$

where:

t_{ppri} – total correct operation time for the ith line [h]; i=1, 2, 3,
n_{pp1} – number of evenings of correct operation of the ith line; i=1, 2, 3.

MTTR is the mean time needed to repair the equipment. Each "repair time" starts when the equipment fails and ends when the equipment starts to run according to its standard operation cycle. The MTTR is calculated according to the following formula:

$$\mathrm{MTTR}_i = \frac{t_{awi}}{n_{ni}}$$

where:

t_{awi} – total time of repair of the ith line [h]; i=1, 2, 3,
n_{ni} – number of repairs of the ith line; i=1, 2, 3.

Calculation of MTTR for furnaces P1, P2, P3

The analyses indicate that the failures of furnaces take up the most failure time of the ith line. Consequently, this subassembly of each line was analysed in detail.

Calculation of MTTR for the ith furnace, i=1, 2, 3:

$$\mathrm{MTTR}_{Pi} = \frac{t_{awPi}}{n_{nPi}}$$

where:

t_{awPi} – total time of repair of furnace Pi [h],
n_{nPi} – number of repairs of furnace Pi.

Production line 1 - PL1

MTBF for production line PL1:

$$\mathrm{MTBF}_1 = \frac{t_{ppr1}}{n_{pp1}} = \frac{5634}{45} = 125{,}2\ \mathrm{h\ /\ year}$$

MTTR for production line PL1:

$$\mathrm{MTTR}_1 = \frac{t_{aw1}}{n_{n1}} = \frac{1126{,}5}{53} = 21{,}25\ \mathrm{h\ /\ year}$$

MTTR for furnace P1:

$$\mathrm{MTTR}_{P1} = \frac{t_{awP1}}{n_{nP1}} = \frac{849}{39} = 21{,}77\ \mathrm{h\ /\ year}$$

Similar calculations of MTBF and MTTR were made for production lines PL2 and PL3 and for furnaces P2 and P3.

Table 5 includes information obtained during the monitoring of the operation of these three furnaces.

Figure 9 presents the share of failures on individual furnace parts (for lines PL1 and PL2).

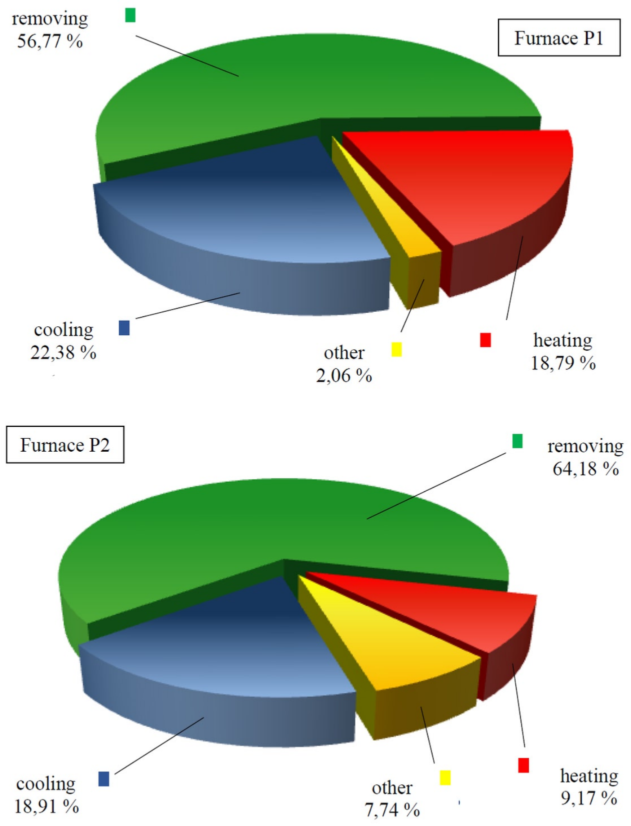

Fig. 9. Percent share of time of individual failures for furnaces P1 and P2 (own study)

Table 5. Failure times of furnaces P1, P2, P3

			Line PL1 – Furnace P1	**Line PL2 – Furnace P2**	**Line PL3 – Furnace P3**
Total failure time [h]			1126,5	509,5	1331,5
Furnace			**Furnace P1**	**Furnace P2**	**Furnace P3**
Components of the furnace repair time	cooling	[h]	190	66	187
		[%]	22,38	18,91	18,80
	slagging	[h]	482	224	629,5
		[%]	56,71	64,18	63,30
	heating	[h]	159,5	32	156
		[%]	18,79	9,17	15,68
	other	[h]	17,5	27	22
		[%]	2,06	7,74	2,21
	total	[h]	849	349	994,5
		[%]	75,37	68,50	74,69

The data from the one-year monitoring and the analyses allowed calculating the indices chosen for the system evaluation. The summary results of the studies of the production lines are presented in Table 6.

Diagrams (Fig.10, 11 and 12) present the sum may of indices calculated for three studied lines PL1, PL2 and PL3.

Table 6. Summary results for individual production lines

	Production line PL1	Production line PL2	Production line PL3
Failure time [h/year]	1126,5	509,5	1331,5
Failure time [%]	12,86	5,82	15,20
Planned downtime [h/year]	1999,5	996	797
Planned downtime [%]	22,83	11,37	9,10
Correct operation [h/year]	5634	7254,5	6631,5
Correct operation [%]	64,31	82,81	75,70
OEE [%]	**70,13**	**74,62**	**70,13**
MTBF [h/year]	**125,2**	**190,9**	**150,72**
MTTR [h/year]	**21,25**	**10,38**	**26,11**

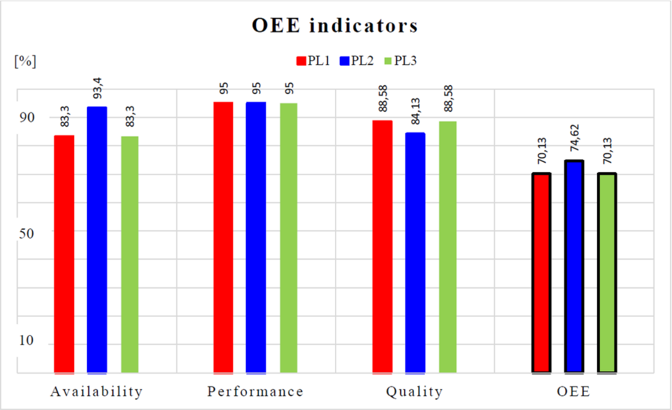

Fig. 10. Summary of OEE indices for studied lines (own study)

5. Summary

The methodology proposed in the paper allowed a multicriterial analysis of the system operation after modernization. The analysis of the number and reasons of process lines downtimes allowed determining the limits of utilization of resources on the disposal of the company and determining the areas in which the improvements should made. One of the conclusions is that the availability D as a parameter whose improvement should be a priority.

The failure times for individual lines differ – for lines LP1 and LP3 the times are significantly longer than for line LP2. The reason is the different technology. The line LP2 is Adapted only to the processing of zinciferous sludge, and the batch material for the remaining lines can also be the dust from electric steel-melting shops. Other physical

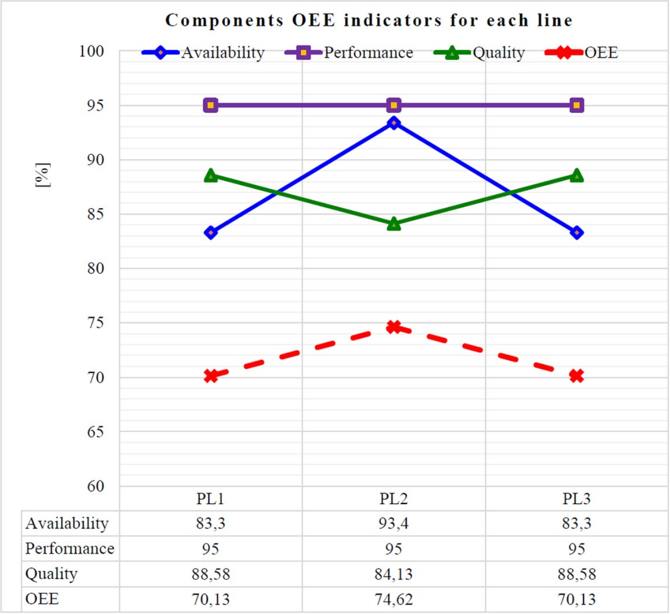

Fig. 11. Component indices and OEE for studied lines (own study)

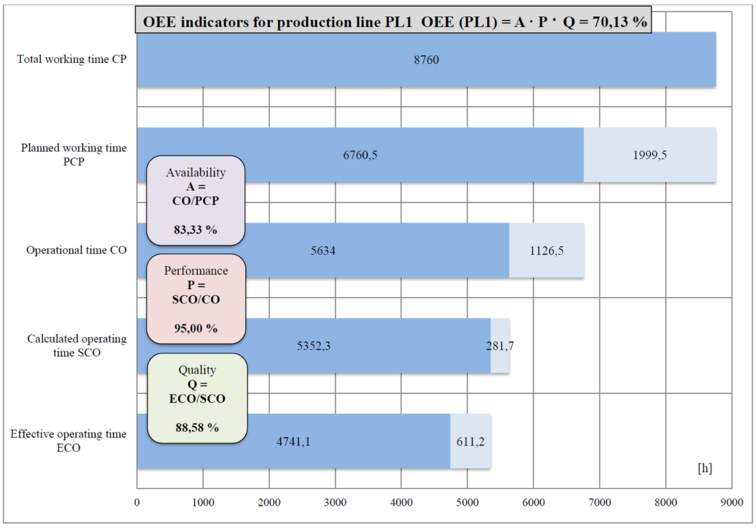

Fig. 12. Summary of OEE indices for production line PL1 (own study)

and chemical properties of the batch and somewhat different course of the process affect, inter alia, the growth rate of deposits inside the furnaces. The analysis proved that this is the most frequently occurring reason for the failures of these devices.

The assignment of the number and times of failures to individual subassemblies of modernized lines allowed indicating rotary furnaces as the most problematic components in terms of unplanned downtime. The failures of this equipment are responsible on the average for 72,83% of failure times on each line. The most time-consuming is the restoration of the equipment of equipment efficiency after the stoppage related to the occurrence of ring deposits. The average MTTR for furnaces is as high as 23,31 h/year. Consequently, technical solutions should be sought to limit the losses resulting from it. One of the suggestions is to use the Winchester industrial gun to speed up the deposit removal.

One of the effects of the technological process modernization was to obtain the European process effectiveness level. For systems producing products from production waste, OEE = 70% was assumed as a satisfactory OEE indicator. The measure of the achievement of this task was the OEE index for each studied production line.

The obtained results are satisfactory:

$OEE_{LP1} = 70{,}13\ \% > OEE_{min} = 70\ \%$,

$OEE_{LP2} = 74{,}62\ \% > OEE_{min} = 70\ \%$,

$OEE_{LP3} = 70{,}13\ \% > OEE_{min} = 70\ \%$.

At the same time, the limit values of average repair times and correct operation were adopted (expert knowledge):

MTTRmax = 30 h and MTBFmin = 125 h, which means that the indicators obtained for all three lines are within the adopted criteria (Tab. 6). Therefore, it can be concluded that the evaluation of the system operation after the modernization is acceptable.

The indices only slightly differ from the word level (75-80 %), which, taking into consideration the complexity of the analysed technological process, can be seen as a satisfactory result. This fact justifies the modernization and indicates that its effectiveness. At the same time, however, efforts should be made to improve the current state, particularly in terms of availability of production lines. the achieved availability level for lines LP1 i LP3 (83,3 %) requires a significant improvement.

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