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RISK ANALYSIS IN MAINTENANCE PROCESSES

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A B S T R A C T
The article aims to present practical methods for prioritising the activities of maintenance departments based on the Pareto analysis and the failure risk analysis. Based on the collected data on the number of observed failures and their removal times, commonly known reliability indicators were determined, which were then used to estimate the probabilities and consequences of failures in terms of the risk of loss of production continuity. Based on commonly collected failure data, the developed methods allow proposing to the maintenance departments the sequence of maintenance and repair work to be undertaken in terms of minimising the risk of failure. Risk analysis is somewhat commonly used in the practice of maintenance departments (e.g. RBI, FMEA, ETA, FTE, HIRA). The added value of this work is the use of reliability indicators for estimating the values of risk components, i.e., probability and consequences. The method was developed on the basis of operational data collected in one of the plants of the dairy cooperative and, after assessing the effects of its implementation, it was implemented in other enterprises of the cooperative.

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INTRODUCTION

In ancient times, the failure-free use of technical inventions was the intention of their creators who also understood that this effect was impossible without periodic, more or less complex maintenance activities. Archaeological findings in prehistoric burial places include, e.g., chariots with traces of grease on their axles, and — speaking in modern terms — catalogues of vegetable oils and animal fats to be used as lubricants.

Throughout history, the concepts of servicing technical facilities have changed. Until the Second World War, such services were mainly understood (apart from cleaning and the aforementioned lubrication) as a reaction to damage. In times of cheap and readily available labour, the reactive approach was predominant. It meant that machines and devices were serviced only when their technical condition required it. Therefore, maintenance activities were most often performed as a reaction to a failure.

In the following decades, machines grew much more complex, making a greater impact on the continuity of production. In the event of a failure, it was no longer possible to replace the operation of these machines with human force, and downtime caused increasingly more economic losses. Along with the increase in the complexity of machine construction, preventive and prognostic concepts emerged, but they still referred to the effectiveness of maintenance activities, i.e., eliminating failures and maintaining the production continuity. Since the end of the last century, the increasing importance of operational efficiency, safety of people and the environment, compliance with the law and standards, and more recently, sustainable development have been recognised.

Maintenance tasks are interdisciplinary. Not only they consist of technical issues (degradation, wear, diagnostics, technical and technological progress) but also legal, normative and managerial issues, which must be resolved to achieve production, quality, environmental and work safety goals. The list of maintenance attributes is no longer limited to the ability to efficiently use workshop tools and quickly locate damage. The contemporary aspects of maintenance include the origin and forecasting of a technical condition, product quality, the safety of people and the environment, and technical and technological development. Such an approach to maintenance processes creates the need to develop or adopt appropriate tools and methods that will allow making effective and efficient decisions regarding the determination of the sequence and scope of maintenance, repair or investment activities.

1. LITERATURE REVIEW

The concept of maintenance appears in terms of inevitable costs which, according to various sources, amount to as much as 5% of the company's turnover, constituting 4–15% of the production costs and about 18% of the inventory value depending on the industry (Mikler, 2008). Some sources estimate that the cost of living amounts to 10–40% (Maggard & Rhyne, 1992), 15–50% (Coetzee, 2004), and even 15–70% (Bevilacqua & Braglia, 2000) of production costs. According to Ahlmann (2002), the costs of maintaining machinery in Sweden accounts for 6.2% of the company's turnover. According to Wireman (1990), 30% of the costs incurred for maintenance arise from improper planning of works and related overtime. The actual costs incurred can be much higher.

Machine failure may entail financial losses not only because of the necessity to remove it but also due to the lack of planned production or penalties related to failure to meet deadlines or environmental pollution (Todinov, 2006). Increasingly more often, insurance companies require maintenance, which is safe in the economic, environmental and health-and-safety terms, basing insurance rates on the effectiveness of this process. Enterprises with high organisational and technical culture are therefore changing their attitude to maintenance processes and ceasing to classify them as costs that need to be minimised, perceiving them as costs that can and must be managed instead. Concepts of proactive maintenance, such as TPM, RCM, RBI, consist of monitoring the technical condition of machines, introducing technical diagnostics, and device operators. These concepts, as well as various approaches to the principles of maintenance, have been widely described in the literature (Żółtowski & Niziński, 2010; Legutko, 2010; Niziński & Michalski, 2007; Legutko, 2007; Pintelon et al., 2006; Żółtowski & Tylicki, 2004; Żurek, 2004; Szpytko et al., 2003; Swanson, 2001).

Enterprises with advanced organisational culture and technologies recognise that not only maintenance processes may have a significant impact on the production output, costs and quality of the final product but also the safety of people and the environment. Maintenance is perceived as an important element of sustainable development (Szczuka & Drożyner, 2015; Jasiulewicz-Kaczmarek & Drożyner, 2013; Drożyner et al., 2011; Farrington-Darby et al., 2005; Fei & Honghui, 1998). Maintenance services are becoming an indispensable element of most business processes, such as production planning to ensure continuity, logistics and sales, environmental protection or HR processes (competences, authorisations, staff working hours), including occupational health and safety.

Besides, maintenance services are responsible for (right and wrong) decisions regarding required maintenance and repair activities, such as machine inspec-

tion, alignment or balancing. Their choice of an operation strategy or purchasing policy may either positively or negatively influence technical and technological development and, as a consequence, the efficiency and effectiveness of the entire enterprise. Therefore, maintenance is a part of such standards as ISO 55001:2014 on asset management. The guidelines for the implementation of an asset management system contained in the ISO 55002 standard suggest the use of such methods and tools as RCM, FMEA, HAZOP, and RCFA (Root Cause Failure Analysis). The comparison of the requirements of ISO 9001 and ISO 55001 in terms of maintenance processes and, more broadly, operation reveals that infrastructure (physical assets) is treated objectively in the ISO 9001 standard (as an intermediary). In contrast, ISO 55001 treats the assets as the main subject and the purpose of action.

The quality standard refers to the infrastructure instrumentally as one of many factors influencing the quality of the product or service. The requirements for infrastructure generally relate to the effectiveness of maintenance, which aims to ensure timely service considering the risk of a potential failure and downtime, and, sometimes, also the quality requirements for the product, which is potentially at risk due to inadequate technical condition of the facility. The process approach to these issues — although ensuring greater operational efficiency — is not required directly and is the sole decision of the entrepreneur.

The ISO 55001 standard specifies all elements of the process approach to infrastructure management, i.e., requirements for the setting (organisation context), planning, identifying measures, and ensuring resources. Also, it concerns typical systemic actions, such as internal audits, management reviews, corrective, preventive and improvement measures. The standard considers assets as a value that can and must be managed rather than inevitable costs. This standard is in line with the proposed (Jasiulewicz-Kaczmarek & Drożyner, 2011; Jasiulewicz-Kaczmarek & Drożyner, 2013; Drożyner et al., 2013) and the model of machine maintenance processes.

Companies that have implemented formalised management systems for quality, environmental protection, health and safety, etc., are obliged to meet the requirements of relevant standards for continuous improvement. Various tools and methods are used in such activities, e.g., brainstorming, histograms, 5 Whys, the Pareto analysis, the Ishikawa diagrams, and the G8D method (Starzyńska et al., 2010; Mazur & Gołaś, 2010). These tools are generally used to improve management and production processes, and, rarely, auxiliary processes, such as maintenance. Meanwhile, a good product is not enough for a business to maintain a position in the market. Nowadays, competition demands greater efforts, and enterprises that do not minimise losses in production have difficulty with staying in the market (Jasiulewicz-Kaczmarek, 2013; Stanek et al., 2011; Saniuk et al., 2015). Therefore, cost optimisation should apply to all processes, especially those that may generate high costs (Stuchly, Jasiulewicz-Kaczmarek, 2014; Pałucha, 2015; Knights, 2001; Obora, 2008).

The widespread use of classical analysis tools for maintenance processes began with the advent of the TPM (Total Productive Maintenance) concept. The tools are used in maintenance to analyse the causes of damage (5 Whys, the Ishikawa diagram (Chang & Lin, 2006)), the prioritisation of maintenance activities (the Pareto analysis (Borris, 2006)), the process improvement (brainstorming (Drożyner & Hoffa, 2015)). The tools have been practically used in the railway (Kumar et al., 2008), aviation (Al-kaabi et al., 2007; Vassilakis & Besseris, 2009), automotive (Holtz & Campbell, 2003), metallurgy (Gajdzik, 2014) and petrochemical (Prasanna & Desai, 2011) industries.

The maintenance of machinery and equipment depends on the context of the enterprise, its goals, structure, internal limitations and external conditions. Components of the maintenance are the result of (1) units targeted by activities, i.e., specific machines and their modules that require inspection, maintenance, and repair; (2) the company's status in relation to the environment, in which it operates; (3) goals that reflect the strategic importance of the company's maintenance; (4) profile of maintenance tasks; and (5) the results achieved in relation to the expected value. The effectiveness of maintenance management in the enterprise is significantly impacted by such factors as the risk assessment of emergency events, the selection of an operational strategy, and the determination of time intervals and resources necessary to implement the tasks resulting from the adopted strategy (Jasiulewicz-Kaczmarek & Bartkowiak, 2016). The new trend of maintenance management has shifted from time interval-based maintenance to risk approach-based maintenance. Risk assessment integrates reliability with safety and environmental issues and can, therefore, be used as a decision-making tool in preventive maintenance planning (Ratnayake & Antosz, 2017; Gill, 2017; Gallaba et al., 2019; Hameed et al., 2019; Özcan et al.,

Tab. 1. Risk analysis tools used for maintenance

Risk Tool	Description	Sample publications on the issue
ETA	Event Tree Analysis — a method for describing the consequences of the superior event, illustrating the progression of events from the initial event to the final event, with particular emphasis on the moments that are decisive for the condition of the facility (installation). It is the primary method of creating an object model for threat analysis	Ahmadi et al., 2008; Mareş et al., 2017
FTA	Fault Tree Analysis — a qualitative method of risk analysis using the structure of logical trees, allowing for modelling the course of a failure and then its analysis. An FTA diagram illustrates causes, the result of which are referred to as uncertain events or risk	Gharahasanlou et al., 2014; Vaurio, 2010
FMEA	Failure Modes Effects Analysis — a method that consists of analytically determining the cause-and-effect relationships of potential product defects and considering the criticality (risk) factor in the analysis. Its aim is to consistently and systematically identify potential product/process defects, and then eliminate them or minimise the related risk	Sutrisno et al., 2015; Onodera & Katsushige, 1997; Braaksma et al., 2013; Mikołajczyk, 2013; Mańka, 2015; Ennouri, 2015
HAZOP	Hazard and Operability Studies, in other words, the analysis of threats and operational capabilities, is based on the PN-IEC 61882 standard. It is often used in the design of new facilities and installations, modernisation of facilities, installations or processes	Hu et al., 2012; Crawley &Tyler, 2015
HIRA	Hazard Identification and Risk Assessment — risk assessment tool that can be used to assess which hazards pose the greatest risk in terms of how likely they are to occur and how great their potential impact may be	Purohit et al., 2018; Liberti et al., 2015
GOFA	Goal-Oriented Failure — analysis and a hazard identification technique that uses selective features from Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) to identify the causes of failure of a specific target	Yi et al., 2017; Yi et al., 2016
RBI	Risk-Based Inspection — determining the scope and methods of testing, allowing to determine the risk associated with the operation of technical devices, based on the results of quantitative risk analysis	Arunraj & Maiti, 2007; Khan et al., 2004; Khan & Haddara,2003
RCM	Reliability-Centred Maintenance — determining the necessary maintenance activities in the operational efficiency of the machine or device, considering the conditions of use	Hauge et al., 2001; Braglia et al., 2019

2019; Michalak, 2017). Risk-based maintenance planning minimises the probability of a system failure and its consequences related to safety, economy and the environment (Jasiulewicz-Kaczmarek et al., 2020). It assists management in making the right maintenance investment decisions, which, in turn, results in better use of existing production equipment. In recent years, there has been a growing interest in the use of risk analysis and risk-based (informed) approaches for guiding decisions on maintenance (Table 1).

2. Research Methods

One company from the food processing industry (dairy) was used to compile data on the frequency and duration of emergency downtime. During the analysed period (20 months), 132 defects were recorded, the removal of which took a total of 241 hours (Table 2).

First, a Pareto analysis was performed for the damage that occurred, considering first the time of their removal and then, their number as a criterion. When conducting the analysis, two variants of the procedure were considered. In the first one (V1), each operated device was studied separately. In the second (V2), whole homogeneous groups of devices (such as tanks) were studied separately (as a single unit). As the Pareto analysis is widely described in the literature (Karuppusami, Gandhinathan 2006; Talib et al., 2010; Miller 2011), the description is not provided in this paper. The results of the analysis are presented in Figs. 1–4.

Tab. 2. List of the frequency and duration of emergency downtime at the enterprise

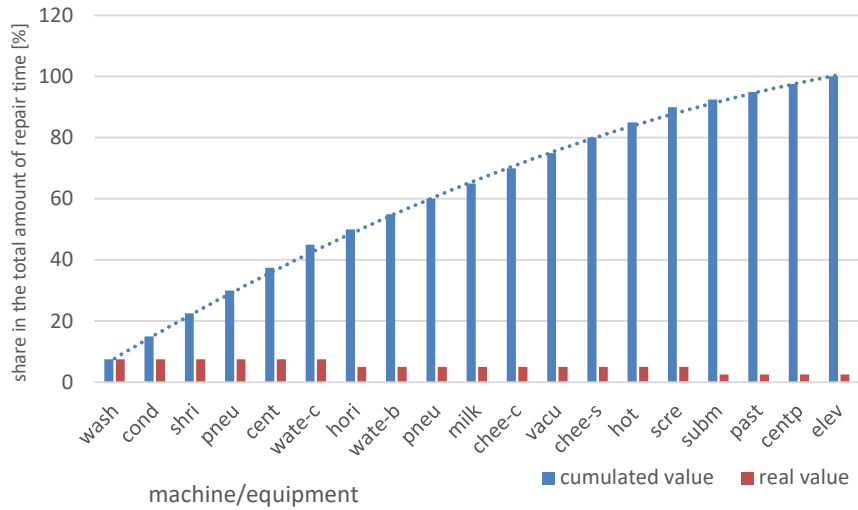| Equipment	Units of equipment	Code of equipment	Number of failures N_i in the analysed period	Number of failures per equipment	Total time T_i of damage removal [h]	Time T_i of damage removal for single equipment [h]
horizontal tank	7	hori	35	5	70	2
submersible pump	20	subm	40	2	40	1
washing station	2	wash	8	4	24	3
condensing unit	1	cond	5	5	15	3
water boiler	1	wate-b	5	5	10	2
shrink wrapping machine	1	shri	3	3	9	3
pneumatic pump for cheese	1	pneu	3	3	9	3
centrifuge LWG-47	1	cent	3	3	9	3
pneumatic press of cheeses	1	pneu1	4	4	8	2
milk collection station	1	milk	4	4	8	2
cheese cauldron	1	chee-c	3	3	6	2
vacuum packing machine	1	vacu	3	3	6	2
cheese slurry pump	1	chee-s	3	3	6	2
hot water pump	3	hot	3	1	6	2
water cooler	1	wate-c	2	2	6	3
pasteuriser - milk - cream	1	past	4	4	4	1
centrifugal pump	1	centp	2	2	2	1
screw compressor	1	scre	1	1	2	2
elevator	1	elev	1	1	1	1
together			132	58	241	40

Fig. 1. Result of the Pareto analysis for the "repair time" criterion in the V1 variant
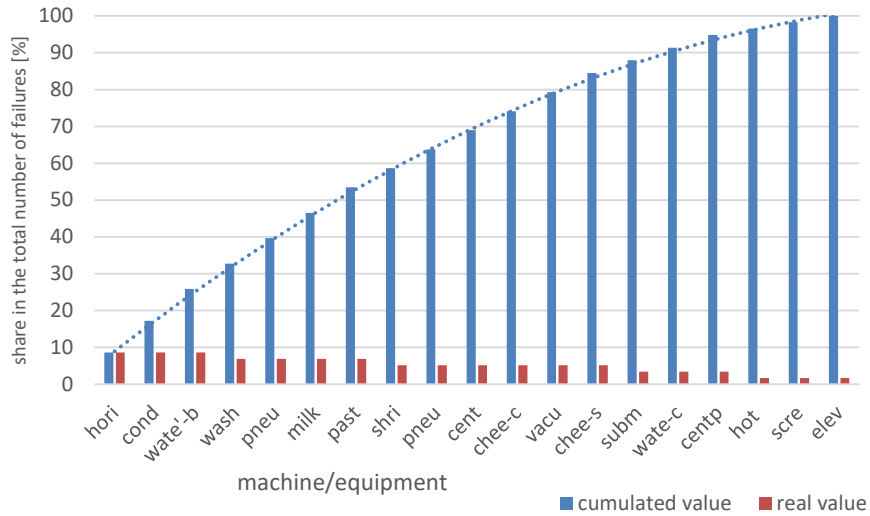

Fig. 2. result of the Pareto analysis for the "number of failures" criterion in variant V1
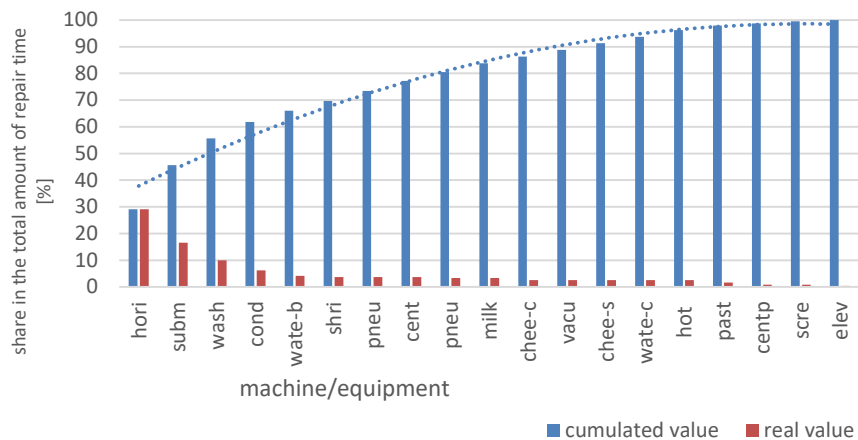

Fig. 3. Result of the Pareto analysis for the "repair time" criterion in the V2 variant
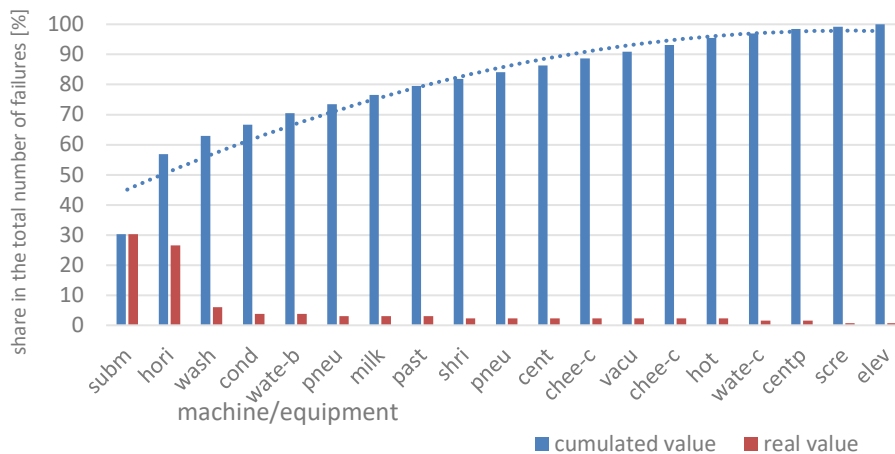
Fig. 4. Result of the Pareto analysis for the "number of failures" criterion in the V2 variant

It was found that in variant V1, when using the repair time criterion, the most important damages with the total share in the criterion of 80% were those that happened at the washing station, the condensing unit and the shrink-wrapping machine. In the case of the failure number criterion, the most important damages were those that were found at the horizontal tank, condensing unit and water boiler. In variant V2, when using the repair time criterion, the most important damages were those that took place were at the horizontal tank, submersible pump and washing station. And using the criterion of the number of failures, the most important damages were those that occurred at the submersible pump, the horizontal tank and the washing station. In the next step, it was decided to carry out the analysis using the method proposed by Knights (2001). This method allows for the simultaneous study of the influence of two criteria as opposed to the traditional Pareto method, where the influence of only one factor can be determined and visualised at one time, as shown in Figs. 1–4.

Figs. 5 and 6 show the location of individual pieces of equipment (their codes) in the coordinate system "number of failures" and "repair time" for both variants of analyses. This type of analysis allows for a certain grouping of equipment from the point of view of the product depending on the frequency and duration of failures. It is possible to easily visualise pieces of equipment, for which failures are chronic (relatively frequent) and those that, even in the case of a single incident, are significant for the company (due to the time required for removal). It was assumed that the threshold value of the number of failures L for chronic failures is:

$$L = \frac{N}{p} \qquad (1)$$

where:

N — total number of damage incidents,

p — number of pieces of equipment (19 in variant V1 and 47 in V2),

and for severe damage, the average repair time K is:

$$K = \frac{T}{N} \qquad (2)$$

where:

T — total damage removal time.

For the collected data, L = 6.9 failures per piece of equipment and K = 1.8 h per failure in variant V1 and L = 2.8 failures per piece of equipment and K = 1.8 h per failure in variant V2 were calculated. These limits are presented in Figs. 5 and 6. Pieces of equipment were classified depending on types of failure, i.e., chronic, major, chronic and serious, and less significant. A logarithmic scale was used to make the chart more readable. "L" — vertical line, "K" — horizontal line.

Based on this approach, the most important pieces of equipment were the shrink-wrapping machine, the centrifuge LWG-47, the pneumatic press for cheeses, the washing station, the condensing unit, the cheese slurry pump, the cheese cauldron, the vacuum packing machine, the pneumatic pump for cheese, the milk collection station, the water boiler and the horizontal tank in variant V1 and the horizontal tank, the submersible pump and the washing station in variant V2. As the use of risk analysis methods is becoming increasingly more
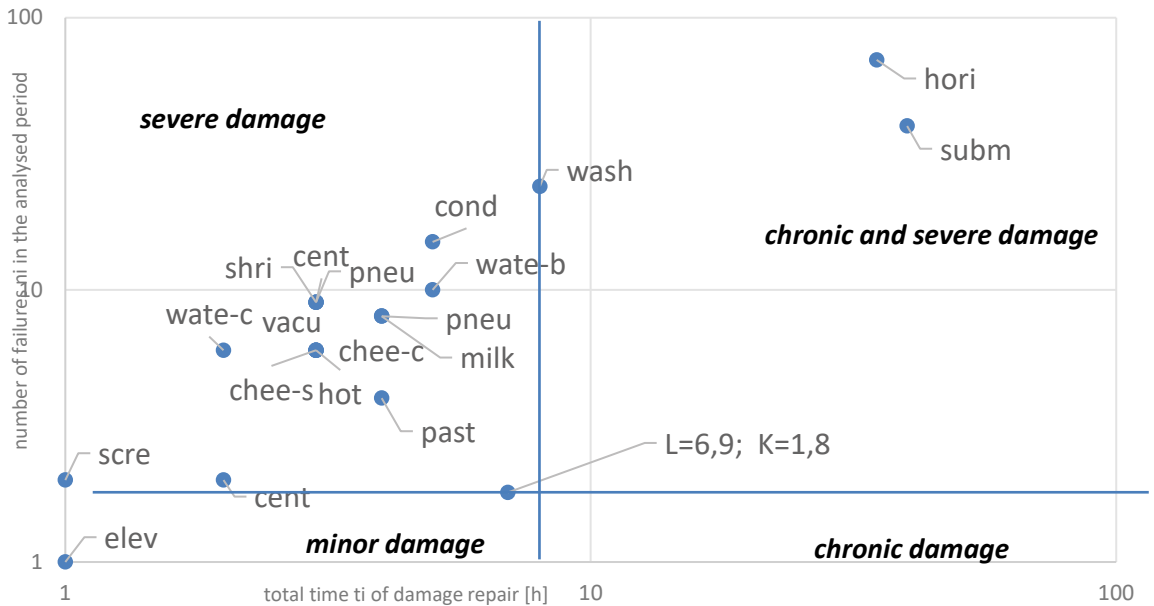
Fig. 5. Tested equipment and the "number of failures — failure recovery time" (V2) system
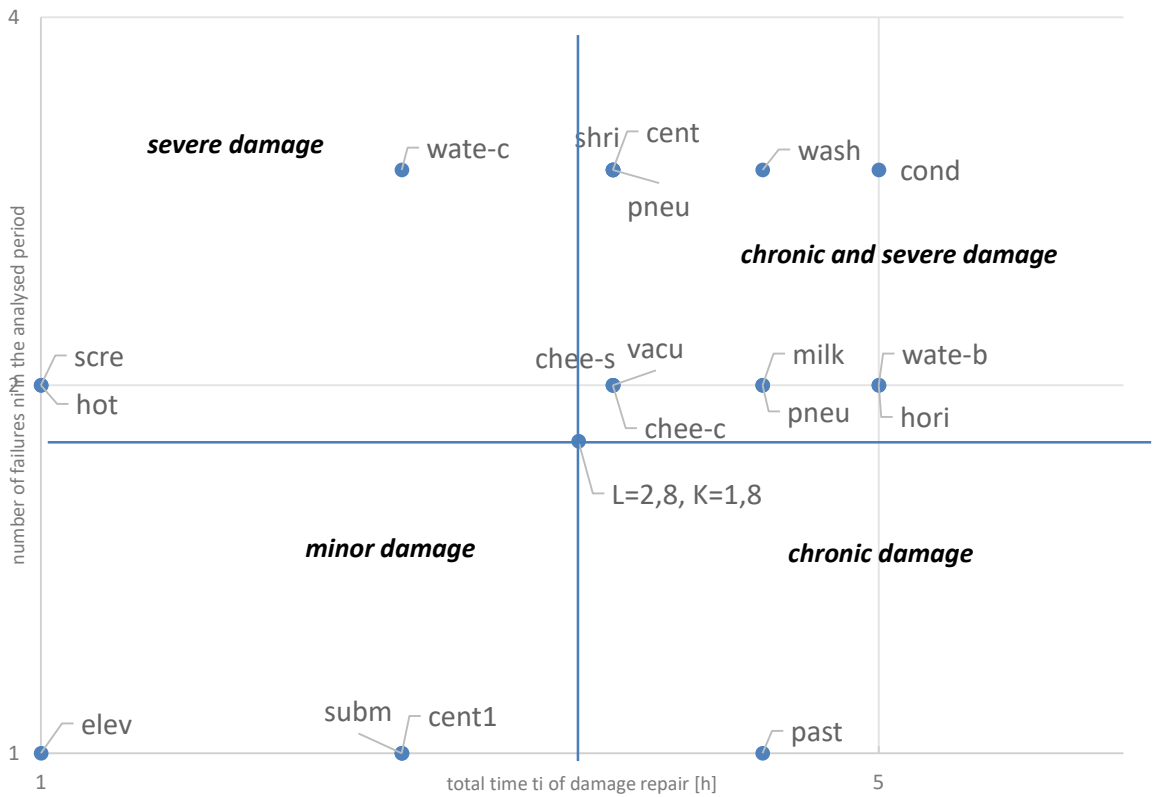
Fig. 6. Tested equipment and the "number of failures — failure recovery time" (V1) system

common for the issues related to machinery and equipment operation, including maintenance (Weber et al., 2012; Aven, 2008; Khan et al., 2004), an original risk assessment method was proposed for further analyses related to failures of individual pieces of equipment with the use of reliability indicators to estimate the probability and consequences of failures. For this purpose, the average times of correct operation between failures for individual pieces (MTBFi) and the share of time ki in repairing the i-th device in the total working time of the company in the examined period T_c (based on accounting data, 4 000 hours of operation in the analysed period were assumed) and the damage stream λ_i for the i-th device, where:

$$MTBF_i = \frac{T_c}{n_i} \qquad (3)$$

$$\lambda_i = \frac{1}{M\,T\,B_i} \qquad (4)$$

$$k_i = \frac{t_i}{T_c} \qquad (5)$$

It was assumed that the measure of the probability of a failure will be the value of the failure stream λ_i, and a measure of consequence — the share of repair time for a given piece of equipment in the total operating time of k_i. The acceptable risk area (the green area in Figs. 7 and 8) was the area limited by the values of λ_i i k_i equal to 1/3 of the maximum values of λ_i i k_i, respectively $\lambda_{accept} = 0.0033$ and $k_{accept} = 0.0058$ (in the variant V1) and $\lambda_{accept} = 0.000433$ and $k_{accept} = 1.04E-07$ (V2). In turn, the increased risk (the yellow area) is determined (arbitrarily) by values that are twice as high.
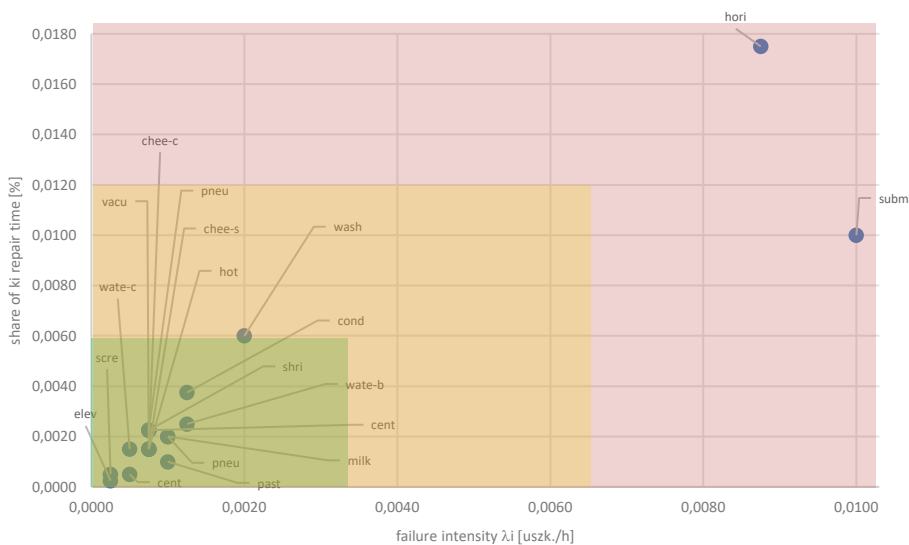

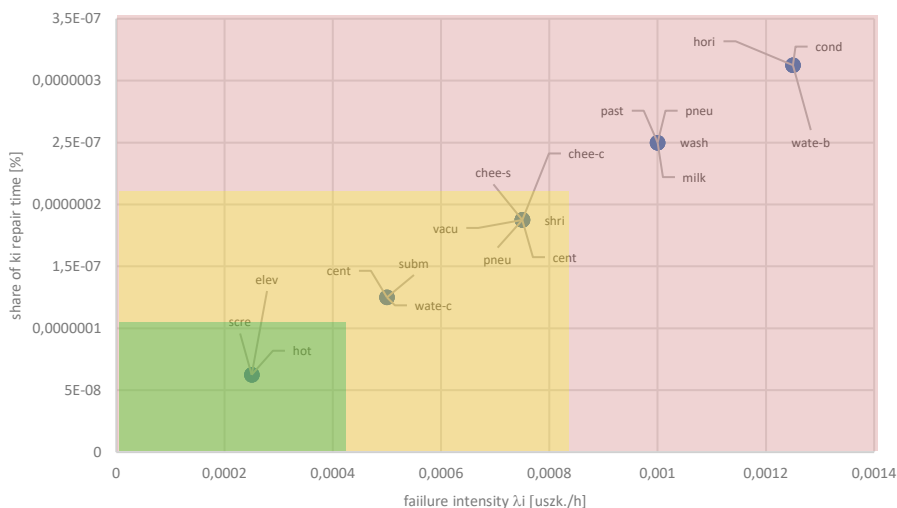Fig. 7. Risk matrix for the tested devices (V2)

Fig. 8. Risk matrix for the tested devices (V1)

Based on these assumptions, in the V1 variant, the pieces of equipment with unacceptable risk were the pasteuriser for milk and cream, the pneumatic pump for cheese, the washing station, the milk collection station, the condensing unit, the horizontal tank, the water boiler. In the case of the V2 variant, the pieces of equipment with unacceptable risk were the horizontal tank and the submersible pump. The results of analyses and calculations are summarised in Tables 3 and 4. The description of the adopted category A for the tested devices is presented in Table 5.

3. RESULTS AND DISCUSSION

Summarising the results obtained in the conducted analyses, it can be stated that the most rigorous in terms of prioritising the tasks of maintenance services is the method of risk analysis in variant V2, i.e., treating groups of homogeneous pieces of equipment as a single piece. The example of submersible pumps and tanks shows that damage to individual devices is not particularly visible in statistics and analyses, and only the grouping of these devices and

Tab. 3. Summary of the analysis results for variant V1

CATEGORY	EQUIPMENT QUALIFICATION IN ASPECT (V1)			
	SINGLE-CRITERIA PARETO ANALYSIS		TWO-CRITERIA PARETO ANALYSIS	RISK ANALYSIS
	BY REPAIR TIME	BY NUMBER OF DAMAGE INCIDENTS		
A	washing station, condensing unit, shrink wrapping machine, pneumatic press of cheeses, centrifuge LWG-47, water cooler, horizontal tank, water boiler, pneumatic pump for cheese, milk collection station, cheese cauldron, vacuum packing machine, cheese cauldron	horizontal tank, condensing unit, water boiler, washing station, pneumatic press of cheeses, shrink wrapping machine, pneumatic pump for cheese, centrifuge LWG-47, cheese cauldron, vacuum packing machine	shrink wrapping machine, centrifuge LWG-47, pneumatic press of cheeses, washing station, condensing unit, cheese slurry pump, cheese cauldron, vacuum packing machine, pneumatic pump for cheese, milk collection station, water boiler, horizontal tank	pasteuriser - milk – cream, pneumatic pump for cheese, washing station, milk collection station, condensing unit, horizontal tank, water boiler,
number of devices	13	10	12	7

Tab. 4. Summary of the analysis results for variant V2

CATEGORY	EQUIPMENT QUALIFICATION IN ASPECT (V1)			
	SINGLE-CRITERIA PARETO ANALYSIS		TWO-CRITERIA PARETO ANALYSIS	RISK ANALYSIS
	BY REPAIR TIME	BY NUMBER OF DAMAGE INCIDENTS		
A	horizontal tank, submersible pump, washing station, condensing unit, water boiler, shrink wrapping machine, pneumatic pump for cheese, centrifuge LWG-47	submersible pump, horizontal tank, washing station, condensing unit, water boiler, pneumatic pump for cheese, milk collection station, pasteuriser - milk - cream	horizontal tank, submersible pump, washing station	horizontal tank, submersible pump
number of devices	8	8	3	2

Tab. 5. Descriptions and comparison of the adopted damage category

CATEGORY	SINGLE-CRITERIA PARETO ANALYSIS	TWO-CRITERIA PARETO ANALYSIS	RISK ANALYSIS
A	damage for which the total share in a given criterion is 80%	severe and chronic damage	damage with an unacceptable risk

their failures shows that they are a serious problem for maintaining the continuity of the company's production. A pure Pareto analysis, especially in the case of small differences in times of correct operation and the number of failures for individual pieces of equipment, is rather of little use as the number of pieces selected in this way is so large that it does not make a significant contribution to the planning of maintenance and repair works.

In maintenance risk analysis tools like RBI or FMEA, fuzzy values such as "very small", "small", etc. are generally used to estimate probability and consequences. Often these values are burdened with a high degree of subjectivity of the authors of these analyzes and result from their personal experiences. In the method proposed in the article, to estimate the probabilities and consequences of damages, "hard" data on times and numbers of failures collected during operation were used. In the method proposed in the article, to estimate the probabilities and effects, "hard" data on the times and numbers of failures collected during operation were used. These data were then processed into commonly known reliability indicators, such as MTBF or failure stream. This means that the adopted values of probabilities and consequences are characteristic of the considered population of machines and devices, and for other populations, they may have completely different values. In this way, it was possible to eliminate the subjectivism of risk assessment and analysis.

Conclusions

The perception of maintenance tasks evolved over time from a purely technical role, focused on strict maintenance and repair activities, through preventive and prognostic concepts to proactive, and even intended to be an element of sustainable development. By analogy with the concept INDUSTRY 4.0, MAINTENACE 4.0 comes into use as a technical, technological and even social equivalent. As a result, maintenance as an interdisciplinary field needs appropriate methods and tools that will allow it to achieve its goals effectively and efficiently.

A characteristic feature of traditional, classic tools used in quality management and process improvement (such as the Pareto analysis or the Ishikawa diagram) is their simplicity, efficiency and practically no cost. They allow the identification of qualitative and sometimes also quantitative relationships between various factors in the production process. Thanks to the use of these methods, it is possible to make decisions that will optimise the use of resources, change the methods of operation and organisation of work, and although they do not create technical or technological progress themselves, they can make a significant contribution. It can be concluded that these tools are mainly applicable to the economic and organisational aspects of maintenance, but they can also identify strictly technical needs, such as creating models for more effective maintenance planning. The article shows how the use of various tools, such as the Pareto analysis, two-criteria Pareto analysis, risk analysis with the use of reliability indicators to estimate the probability of failures and their effects, allows identifying those pieces of equipment whose failures are of key importance for the effectiveness of the production process. It has been shown that the most "restrictive" tool that directs the activities of maintenance services is the risk analysis, which uses operational data that is easy to obtain, i.e., the number of failures and the time required for their removal. It has also been shown that the way of collecting and classifying the collected data is important. Information about the operation of each separate piece should be collected rather than the whole group of pieces operated as one as it may lead to the "blurring" of the problem, which may be important for an enterprise. Naturally, such methods and tools will not make it possible to improve the technical aspect of the maintenance activities related to the prediction and elimination of the effects of various types of wear and fatigue processes taking place in the operated technical facilities. New equipment and methods will be required in such a case, resulting from technological progress and scientific research.

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