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THE REDUCTION IN THE NUMBER OF CO_2 DEFECTS IN THE PROCESS OF OBTAINING BREATHING AIR FOR HYPERBARIC OXYGEN CONDITIONS

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ABSTRACT

Maintaining a stable carbon dioxide content in the process of obtaining breathing air is essential for safe underwater operations and the reduction of the cost of losses resulting from a poor quality product. The paper addresses the modification of the hyperbaric breathing air production process in terms of eliminating harmful carbon dioxide contaminants. It presents the effects of the modifications made to the process in order to minimise the proportion of defects. A description is given of the status of the process before and after the correction in terms of the identified areas of improvement leading to the achievement of the defined critical requirements of the process. Achievement of the objective to rationalise the breathing air production process was confirmed by results of tests carried out at KTPP AMW[1] based on the compressed air supply system of the DGKN - 120 complex[2].

Keywords: process capability, diving breathing air quality, diving gases, measurement systems, process variation, carbon dioxide elimination, air filtration systems for divers.

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INTRODUCTION

The use of validated measurement systems in the study allowed for inferences on the status of the hyperbaric breathing air production process [1]. It was confirmed that the cumulative number of non-conformities at control measurements, of the standardised carbon dioxide pollutants (CO_2)[3] at the process output, significantly exceeded the accepted assumptions of the defined CTQ[4] requirements, i.e. an expected proportion of product defects at the level of $\mathrm{C_{CO_2}} \leq 5\%$. Such process status required the identification and compensation of the causes of its disturbances and the evaluation of the impact of the controlled parameters in order to achieve the minimum of the objective function understood as: $\mathrm{Y_1}$ normalised content of CO_2 within the tolerance limits $\mathrm{C_{CO_2}} \in [0 \div 500]\mathrm{ppm}$, where $\exists_{\mathrm{x_1..x_i}} \mathrm{C_{CO_2}} \leq \mathrm{C_{CO_2}^{max}}$ and $\mathrm{Y_2}$ seen as the meeting of the requirement for the system set and filtration protection time $\mathrm{t_p} \in [50 \div 100]\mathrm{hours}$. The results of the process capability assessment prior to rationalisation, will not be presented here, as they have already been described in detail in a previous paper [2]. Analysis of a series of measurement data distributed in time in respect to the defined critical level of the proportion of irregularities $\overline{Y_1} \leq 5\%$ indicated that the average occurrence of product defects in the sample was as high as $17{,}74\%(2{,}43\sigma)$[5] with regard to exceeding of the permitted standardised carbon dioxide limit, i.e. $C_{CO_2} \gg 500ppm$ for $cl.II$ acc. to $NO-07-A005:2020$and PN-EN 12021:2014-8 [4]. This corresponds to the level of process capability indices: C_p, $C_{pk} = [0{,}86, 0{,}51] < 1$ and $P_p, P_{pk} = [0{,}63; 037]min < 1$[6] [2]. Thus, this shows that the process of breathing air treatment carried out by the tested set of compression and filtration system is unstable and inefficient [5]. The defined minimum failure-free operation time of the compression and filtration system, understood as the filter cartridge breakthrough time, should be a minimum of $Y_2 = \left[\, t_p \geq 3msc,\ t_p \geq 50 \div 100\ hours \right]$[7] [3].

The observed time of protective operation of the bed up to the first breakthrough does not meet the critical requirements of CTQ[8] and amounted to $Y_2 = 19{,}30\mathrm{hours} \ll 50\ hours$, while the secondary breakthrough of the bed occurred on average after approximately $\overline{t_p}$ ≈102 minutes of operation of the until from restart [5]. Due to the scale of the problem, elimination of the negative product quality to meett CTQ requirements will not be possible without a modification of the current technology[9] of carbon dioxide elimination[10] [5]. It was hypothesised that regaining process control and minimising the proportion of CO_2 defects requires identification of areas of improvement, verifiation of the effects of controlled parameters on process response and implementation of corrective modifications[11]. The lack of process capability indicates that the state-of-the-art. And redundant filtration systems used[12] do not have sufficient resistance and (robustness)[13] to changes in environmental parameters and do not ensure a product of the required quality.

It was initially assumed that the loss of process capability occurs mainly when the normalized contaminant content in CO_2 in the atmosphere exceed the defined critical requirements in NO-07-A005:2020 i.e. $C_{CO_2} > 500ppm$[14]. The identified constraints resulted in failure to meet the declared nominal parameters of the system, both in terms of the duration of protective operation and the observed number of defects in the production process[15].

WORK OBJECTIVE

The objective of this work is to meet the defined critical process requirements CTQ in terms of reducing the number of CO_2 defects[16] in the process of obtaining breathing air for hyperbaric oxygen conditions from the observed level of $17.74\%(2{,}43\sigma)$ to $\leq 5\%\ (3{,}14\sigma)$ with simultaneous extension of the protective operation time to $Y_2 = \left[\, t_p \geq 3msc,\ t_p \geq 50 \div 100\ hours \right]$ [5]. The lack of process capability and stability over time indicates the need to regain control of the process and provide opportunities to control and improve it.

RESEARCH MATERIAL AND METHODS

During the analysis, a process map was developed and analysed, identifying a number of probable causes for exceeding the CTQ requirements which were subjected to $FMEA$ risk analysis[17], tab.1. The key threats to the process were identified as the intake of difficult-to-remove contaminants, unreliable periodic monitoring of the process condition using simple indicator systems with insufficient metrological properties, loss of sorption capacity of the filter bed and errors in operator compliance with $SOPs$,[18] tab.2. The share of the impact of the risks was confirmed by the observations collected during the monitoring period of the production process, which are included in the $PARETO$ diagram, fig.1. The process risk analysis $FMEA$, [6], showed that the modification of the sorption process and the use of reliable threshold measurements [7], together with the application of alarm systems, can lead to a reduction in the RPN[19].

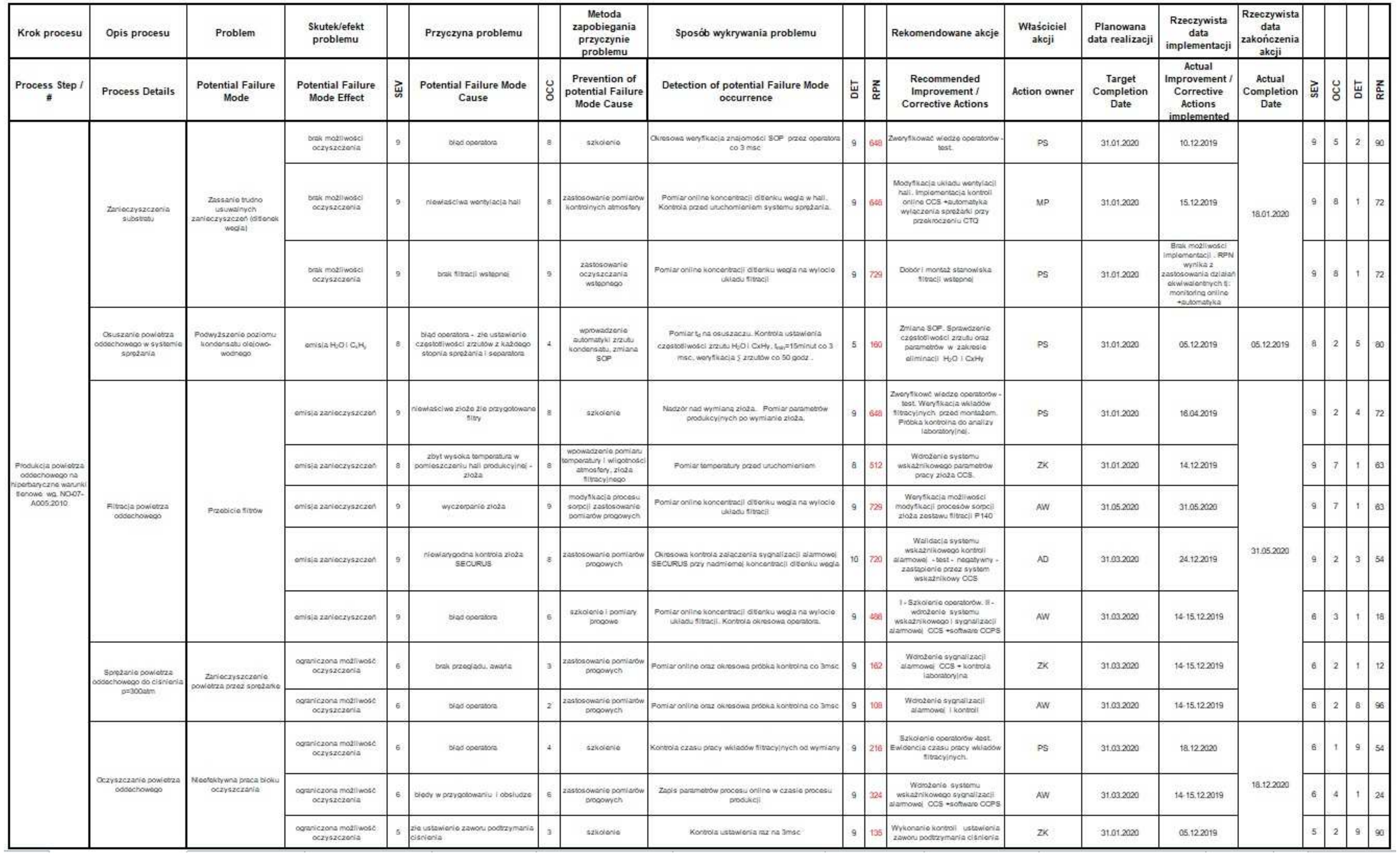
Consequently, areas of process improvement were preliminarily identified to achieve the defined CTQ requirements. It was assumed that:

- proper training and revision in $SOPs$,
- adequate oversight of the operation of the compression and filtration system,
- introduction of online threshold process measurements for the determination of CO_2 content in the control sample,
- modification of sorption technology processes for the purpose of elimination of CO_2 contamination,will effectively reduce the RPN risk levels identified for the process of providing air for hyperbaric and oxygen conditions.

The changes to the currently used manufacturing technology required the implementation of verification tests confirming the effectiveness of the implemented changes, especially with regard to the modified filtration systems. Qualitative evaluation of the process results was performed using qualified reliable online measurement systems[20] and laboratory methods of instrumental analysis[21] for the breathing air samples collect at $KTPP\ AMW$ and the independent military breathing gas physico-chemical laboratory $WTM\ 1\ RBlog$[22].

Tab. 1

FMEA risk analysis for the process of obtaining breathing air under hyperbaric oxygen conditions.



Krok procesu	Opis procesu	Problem	Skutek/efekt problemu		Przyczyna problemu		Metoda zapobiegania przyczynie problemu	Sposób wykrywania problemu			Rekomendowane akcje	Właściciel akcji	Planowana data realizacji	Rzeczywista data implementacji	Rzeczywista data zakończenia akcji				
Process Step / #	Process Details	Potential Failure Mode	Potential Failure Mode Effect	SEV	Potential Failure Mode Cause	OCC	Prevention of potential Failure Mode Cause	Detection of potential Failure Mode occurrence	DET	RPN	Recommended Improvement / Corrective Actions	Action owner	Target Completion Date	Actual Improvement / Corrective Actions implemented	Actual Completion Date	SEV	OCC	DET	RPN
Produkcja powietrza oddechowego na hiperbaryczne warunki tlenowe wg. NO-07-A005:2010	Zanieczyszczenia substratu	Zassanie trudno usuwalnych zanieczyszczeń (ditlenek węgla)	brak możliwości oczyszczenia	9	błąd operatora	8	szkolenie	Okresowa weryfikacja znajomości SOP przez operatora co 3 msc	9	648	Zweryfikować wiedzę operatorów - test.	PS	31.01.2020	10.12.2019	18.01.2020	9	5	2	90
			brak możliwości oczyszczenia	9	niewłaściwa wentylacja hali	8	zastosowanie pomiarów kontrolnych atmosfery	Pomiar online koncentracji ditlenku węgla w hali. Kontrola przed uruchomieniem systemu sprężania.	9	648	Modyfikacja układu wentylacji hali. Implementacja kontroli online CCS +automatyka wyłączenia sprężarki przy przekroczeniu CTO	MP	31.01.2020	15.12.2019		9	8	1	72
			brak możliwości oczyszczenia	9	brak filtracji wstępnej	9	zastosowanie oczyszczania wstępnego	Pomiar online koncentracji ditlenku węgla na wylocie układu filtracji	9	729	Dobór i montaż stanowiska filtracji wstępnej	PS	31.01.2020	Brak możliwości implementacji . RPN wynika z zastosowania działań ekwiwalentnych tj: monitoring online +automatyka		9	8	1	72
	Osuszanie powietrza oddechowego w systemie sprężania	Podwyższenie poziomu kondensatu olejowo-wodnego	emisja H_2O i C_xH_y	8	błąd operatora - złe ustawienie częstotliwości zrzutów z każdego stopnia sprężania i separatora	4	wprowadzenie automatyki zrzutu kondensatu, zmiana SOP	Pomiar t_d na osuszaczu. Kontrola ustawienia częstotliwości zrzutu H_2O i CxHy, t[illegible]=15minut co 3 msc, weryfikacja ∑ zrzutów co 50 godz .	5	160	Zmiana SOP. Sprawdzenie częstotliwości zrzutu oraz parametrów w zakresie eliminacji H_2O i CxHy	PS	31.01.2020	05.12.2019	05.12.2019	8	2	5	80
	Filtracja powietrza oddechowego	Przebicie filtrów	emisja zanieczyszczeń	9	niewłaściwe złoże źle przygotowane filtry	8	szkolenie	Nadzór nad wymianą złoża. Pomiar parametrów produkcyjnych po wymianie złoża.	9	648	Zweryfikowć wiedzę operatorów - test. Weryfikacja wkładów filtracyjnych przed montażem. Próbka kontrolna do analizy laboratoryjnej.	PS	31.01.2020	16.04.2019	31.05.2020	9	2	4	72
			emisja zanieczyszczeń	8	zbyt wysoka temperatura w pomieszczeniu hali produkcyjnej - złoża	8	wprowadzenie pomiaru temperatury i wilgotności atmosfery, złoża filtracyjnego	Pomiar temperatury przed uruchomieniem	8	512	Wdrożenie systemu wskaźnikowego parametrów pracy złoża CCS.	ZK	31.01.2020	14.12.2019		9	7	1	63
			emisja zanieczyszczeń	9	wyczerpanie złoża	9	modyfikacja procesu sorpcji zastosowanie pomiarów progowych	Pomiar online koncentracji ditlenku węgla na wylocie układu filtracji	9	729	Weryfikacja możliwości modyfikacji procesów sorpcji złoża zestawu filtracji P140	AW	31.05.2020	31.05.2020		9	7	1	63
			emisja zanieczyszczeń	9	niewiarygodna kontrola złoża SECURUS	8	zastosowanie pomiarów progowych	Okresowa kontrola załączenia sygnalizacji alarmowej SECURUS przy nadmiernej koncentracji ditlenku węgla	10	720	Walidacja systemu wskaźnikowego kontroli alarmowej - test - negatywny - zastąpienie przez system wskaźnikowy CCS	AD	31.03.2020	24.12.2019		9	2	3	54
			emisja zanieczyszczeń	9	błąd operatora	6	szkolenie i pomiary progowe	Pomiar online koncentracji ditlenku węgla na wylocie układu filtracji. Kontrola okresowa operatora.	9	486	I - Szkolenie operatorów. II - wdrożenie systemu wskaźnikowego i sygnalizacji alarmowej CCS +software CCPS	AW	31.03.2020	14-15.12.2019		6	3	1	18
	Sprężanie powietrza oddechowego do ciśnienia p=300atm	Zanieczyszczenie powietrza przez sprężarkę	ograniczona możliwość oczyszczenia	6	brak przeglądu, awaria	3	zastosowanie pomiarów progowych	Pomiar online oraz okresowa próbka kontrolna co 3msc	9	162	Wdrożenie sygnalizacji alarmowej CCS + kontrola laboratoryjna	ZK	31.03.2020	14-15.12.2019		6	2	1	12
			ograniczona możliwość oczyszczenia	6	błąd operatora	2	zastosowanie pomiarów progowych	Pomiar online oraz okresowa próbka kontrolna co 3msc	9	108	Wdrożenie sygnalizacji alarmowej i kontroli	AW	31.03.2020	14-15.12.2019		6	2	8	96
	Oczyszczanie powietrza oddechowego	Nieefektywna praca bloku oczyszczania	ograniczona możliwość oczyszczenia	6	błąd operatora	4	szkolenie	Kontrola czasu pracy wkładów filtracyjnych od wymiany	9	216	Szkolenie operatorów -test. Ewidencja czasu pracy wkładów filtracyjnych.	PS	31.03.2020	18.12.2020	18.12.2020	6	1	9	54
			ograniczona możliwość oczyszczenia	6	błędy w przygotowaniu i obsłudze	6	zastosowanie pomiarów progowych	Zapis parametrów procesu online w czasie procesu produkcji	9	324	Wdrożenie systemu wskaźnikowego sygnalizacji alarmowej CCS +software CCPS	AW	31.03.2020	14-15.12.2019		6	4	1	24
			ograniczona możliwość oczyszczenia	5	złe ustawienie zaworu podtrzymania ciśnienia	3	szkolenie	Kontrola ustawienia raz na 3msc	9	135	Wykonanie kontroli ustawienia zaworu podtrzymania ciśnienia	ZK	31.01.2020	05.12.2019		5	2	9	90

Tab. 2

List of the causes and risks of the process. Source: own elaboration.

Code no.	Process risk
1	Absorption of hard-to-remove contaminants
2	Loss of sorption capacity of the filter bed
3	Increased condensate level
4	Air contamination from compressor
5	Secondary pollution from storage systems
6	Incorrect sampling
7	Physical and chemical analysis errors
8	Incorrect setting of the pressure maintenance valve of the filtration set
9	Incorrect compliance with SOP by the operator
10	Faulty filter inserts (out of date)
11	Unreliable process control by simple indicator systems

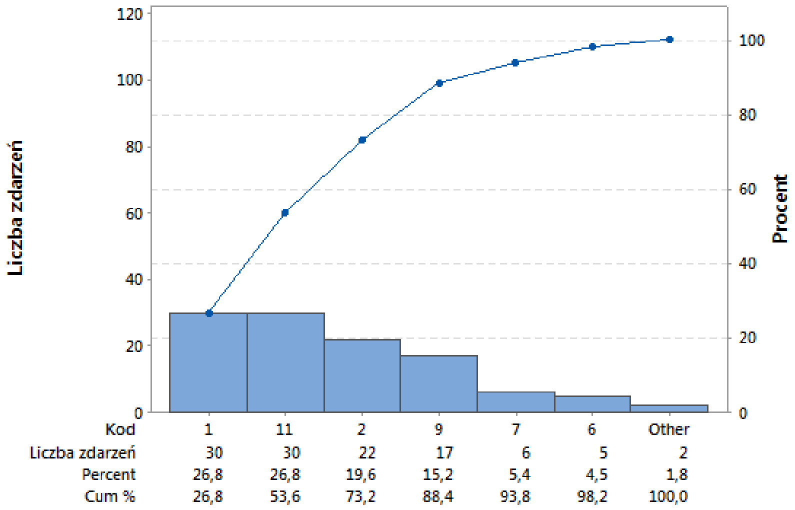


Fig.1 PARETO diagram for the occurrence of process risks. Source: own research.

Given the unsatisfactory state of the process, relationships between its parameters were explored. The work involved the classification and ordering of input and output parameters of the process, controlled and uncontrolled factors that can influence the output variable $Y_1 - C_{CO_2}$ (5). The initial verification of the parameters and the existing correlations was performed based on the selected empirical distribution of the measurement data series obtained after the analysis of the process capability in the measurement phase, fig. 2. The distribution shows a variation in the observed parameters over time leading to a loss of sorption properties of the filter bed in terms of effective elimination of carbon dioxide from the breathing air. The distribution reveals the presence of significant correlations between the controlled parameters, fig.3-4, which allowed to look for the possibilities of creating and verifying a simple multiple regression model for the defined *CTQ*, i.e. the expected critical initial carbon dioxide content $Y_1 - C_{CO_2} \leq 500ppm$, and thus meeting the requirements for the protective time of $Y_2 - C_{CO_2} > 50hours$. With the decision to opt for linear regression analysis, examination was carried out to determine whether a significant linear relationship existed between the variables. In order to improve the current process capability after identifying significant correlations, it was determined which of the analysed parameters (x_1, x_2, x_4, x_7)[23] have an impact on the result Y_1. The decision to choose a regression model affects the precision of the representation of the actual relationships between the variables in the studied process and involves decisions regarding the inclusion of significant explanatory variables, linear, non-linear relationships between variables and the occurring interactions[24].

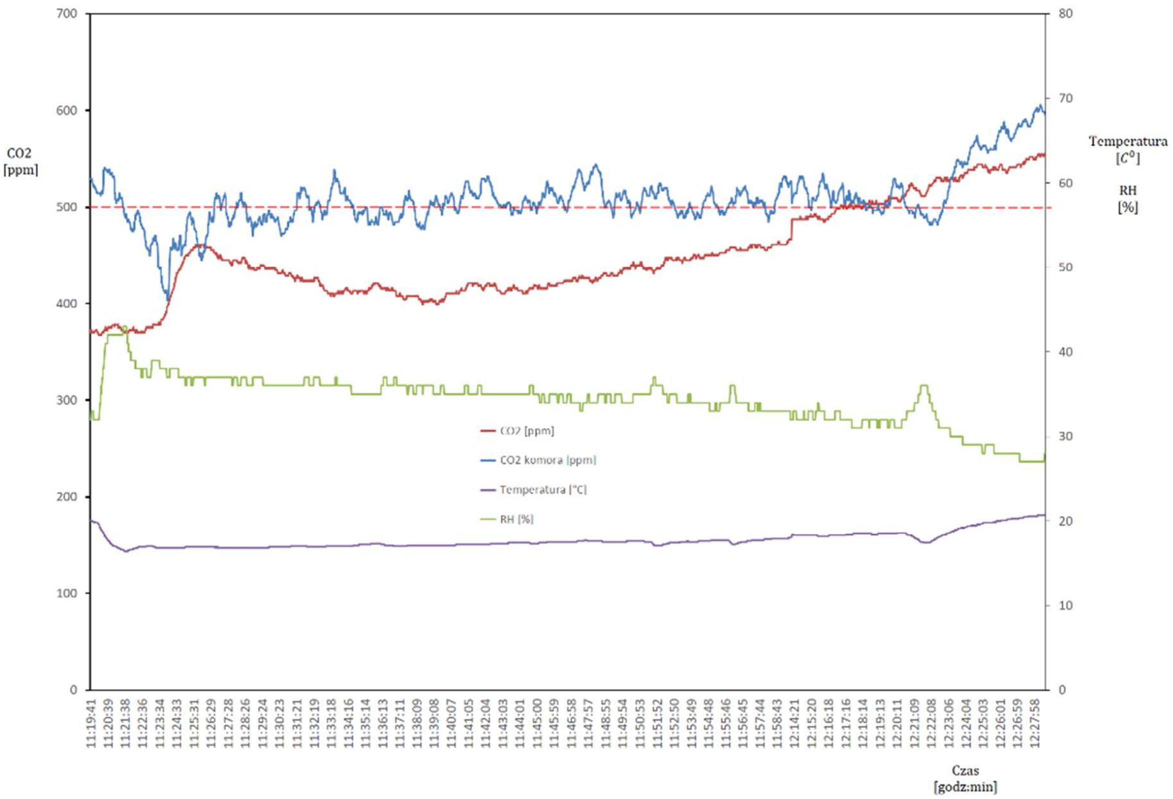
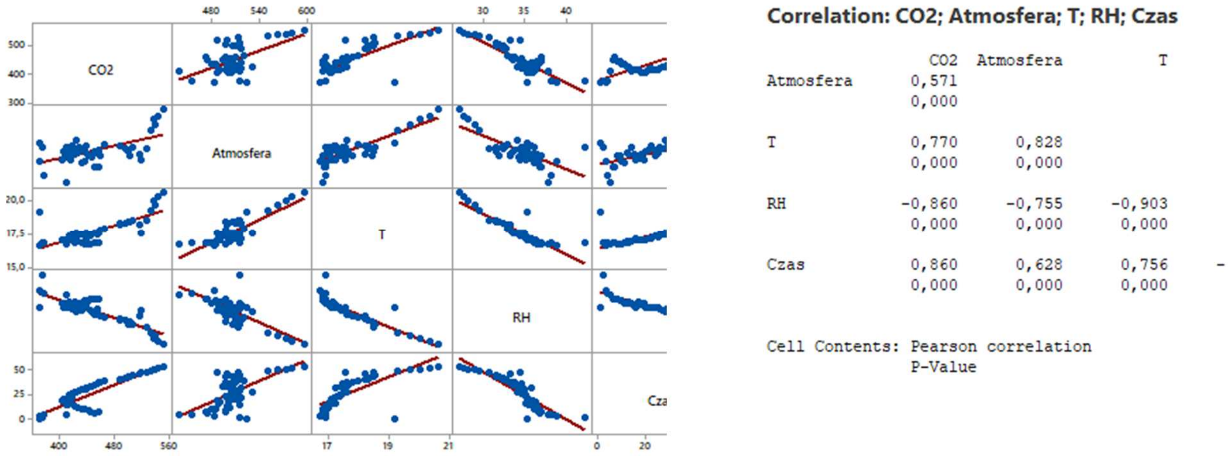


Fig. 2 Distribution of breathing air process parameters selected for correlation analysis as at 02.12.2020. Source: own research.



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Correlation: CO2; Atmosfera; T; RH; Czas

               CO2  Atmosfera        T
Atmosfera    0,571
             0,000

T            0,770      0,828
             0,000      0,000

RH          -0,860     -0,755   -0,903
             0,000      0,000    0,000

Czas         0,860      0,628    0,756
             0,000      0,000    0,000

Cell Contents: Pearson correlation
               P-Value
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Fig. 3-4 Correlation coefficients for breathing air process parameters determined from the distribution of measurements as at 02.12.2020. Source: own research.

Given that the magnitude of the dependent variable Y_1 is influenced by several explanatory variables $Y_1 = f(x_1, x_2,\ x_4,\ x_7)$ an attempt was made to create a model with four explanatory variables [5]. The quantitative account of the correlation between the multiple controlled variables and the dependent variable Y_1 was outlined using a multiple regression model in the general form Y = a + $b_1 \cdot X_1$+ $b_2 \cdot X_2$+ ... + $b_n \cdot X_n$ for the selected 53 groups and $n = 60$ of measurement data series. Given the obtained value of the coefficient of determination $R^2 = 66\%$ and the heterogeneity of the distribution of residual the originally considered model form with four explanatory variables: $Y_1\ = 609 - 0{,}398\, X_1\ +\ 12{,}92 \cdot X_2\ -\ 6{,}56 \cdot X_4\ +\ 1{,}458 \cdot X_7$ was found as insufficient for the prediction. With such an estimation error, it should not be excluded that $Y_1$is also influenced by other uncontrolled factors not included in the model[25]. For empirical data, an analysis of the distribution residuals was performed, which revealed significant discrepancies between the expected value determined from the equation and the actual measurement result. $N = 5$ observations were identified, qualifying them as possible occurrences caused by unknown special causes. A reduction of the regression model was performer by rejection of $n = 5$ measurements, obtaining a goodness of fit of $R^2 = 85\%$, sufficient for preliminary prediction. Compared to the previous model form, a 19,25% higher value of the coefficient of determination R^2 was obtained, thus improving the level of prediction for the output variable Y_1. The form of the model was defined taking into account the lowest possible value of $Mallows'$[26] fit coefficient and the highest value of R^2. After estimating model parameters, defining its final for and verifying its correctness[27], the model was used to predict changes in significant process parameters in the range of settings of $x_1 - C_{CO_2\,a}$, $x_2 - T_a, x_7 - t_{pr}$. For the empirical data analysed, the effect of relative humidity x_4, proved not to be significant, and therefore was not included in the final form of the predictive model described by the formula: $Y_1 = 18{,}7 - 0{,}418\,X_1 + 33{,}67 \cdot X_2 + 1{,}686 \cdot X_7$, tab.3. It was considered capable of predicting the initial value of the parameter settings that would enable achieving the desired value of $Y_1 < 500ppm = f(x_1, x_2, x_7)$ and therefore controlling the process in its refinement phase. The particular steps of the inference process leading to the development and verification of the statistical model will not be cited in detail here, as they will be described separately.

It was decided to confirm the conclusions drawn from the empirical data regarding the significance of the influence of each of the model parameters, tab. 3 in a passive experiment based on an alternative sample of historical data series distributions [8]. Due to the impossibility of forcing the expected set values of the process parameters included in the model[28], changes were not made in a controlled manner, thus not using the classical DOE[29] approach to conduct full[30] or fractional factorial experiments.

The inference was based on the collected distributions of the historical data series, where, in order to confirm the reasons for the differences in the output variable, the relationship between the defined CTQs of the process Y_1, Y_2 and the level of the observed model parameters $Y_1 = f(x_1, x_2, x_4, x_7)$, in two defined process states, i.e.: „good[31] and bad”[32], tab.4. It was arbitrarily assumed that the level of studied parameters in the so-called „good” state is favourable for the process and corresponds to the CTQ requirements, thus being acceptable. The data for $x_1 - C_{CO_2\,a}, x_2 - T_a, x_4 - RH, x_7 - t_{pr} = f(m_s)$ were compared in pairs for the selected model parameters for the for the “good” and “bad” product, respectively.

Tab.3

Overview of the prediction and optimisation results of the regression model with three explanatory variables based on the selected distribution of the measurement data as at 02.12.2020. Source: own research.

No.	*Parameter*	*Result*	*Conclusions*
1	$x_1 - C_{CO_2\,a}$ [ppm]	*positive*	*significant impact parameter included in the model*
2	$x_2 - T_a[C^0]$	*positive*	*significant impact parameter included in the model*
3	$x_4 - RH[\%]$	*negative*	*insignificant impact – rejected parameter*
4	$x_7 - t_{pr} = f(m_s)$	*positive*	*significant impact parameter included in the model*

The variables were expressed as the mean $\bar{x}$ d standard deviation of the distributions σ. t was determined that the verification of the statistical hypotheses concerning the influence of the analysed parameters on process quality and the assessment of the significance of the observed differences for $n = 62$ distributions provided sufficient credibility to confirm the conclusions drawn from the developed statistical model.

Tab.4

Summary of parameters analysed in the passive experiment. Source: own research.

Process „good” for Y_1	*Process „bad” for* Y_1
x_{1D}, x_{2D}, x_{4D}	x_{1Z}, x_{2Z}, x_{4Z}
where: x_5 – operator and $x_6 - m_s =$ const	
Tested hypothesis H_0: the results of measurements of the indicated parameters in a good and a faulty process are not significantly different i.e. they do not affect Y_1. H_1: the measurement results of the indicated parameters in a good and a faulty process differ significantly i.e. they affect Y_1.	
H_0: $\bar{x}_{Di} = \bar{x}_{Zi}$ H_1: $\bar{x}_{Di} \neq \bar{x}_{Zi}$	
Method: $t - Student's$ parametric test for comparison of mean values of $\bar{x}$. F homogeneity variance test Mann Whitney non-parametric test for comparison of Me values.	

The resulting empirical data series of individual parameters for the “good” and “bad” product respectively were compared in pairs, Fig.5.

A preliminary observation of the distributions confirmed that the environmental exceedances of carbon dioxide in the substrate and product exceeded the assumptions made for the design of the filtration systems. Intuitive conclusions were confirmed by testing the hypothesis $H_0: \eta_1 = \eta_2$, against the alternative: $H_1: \eta_1 \neq \eta_2$, dla $\alpha = 0{,}05$ on equality of the medians of the observed carbon dioxide content in atmospheric air. The assumption of normality of empirical data distribution was not met in practice, implying the need to opt for the non-parametric $U\ Mann - Whitney$ statistical test [33,34].

This test does not require equinumericity of groups, normal distribution or homogeneity of variance, thus it lends itself to wide application. Unlike parametric tests, its disadvantage lies in the fact that it does not take into account the results of the variance in the groups tested[35].

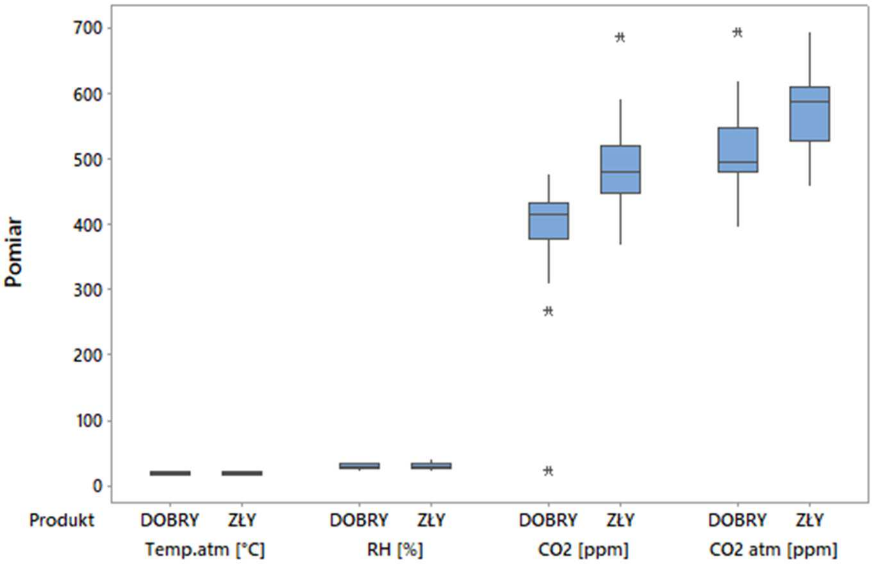
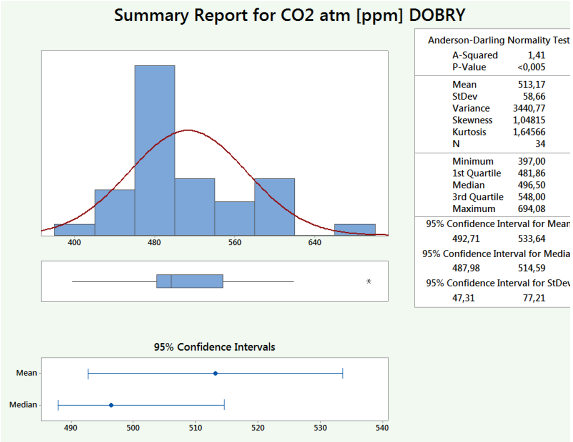
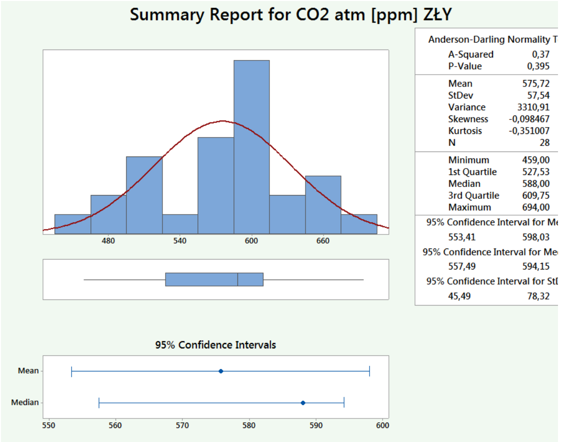
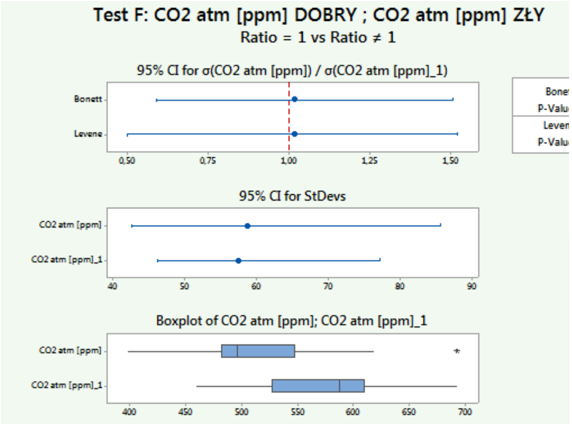


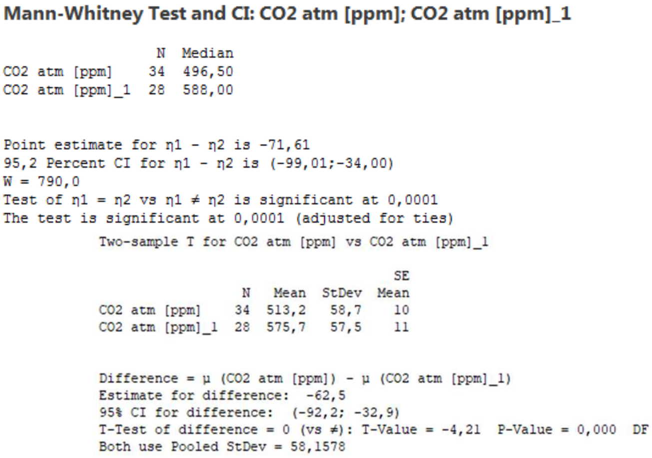
Fig. 5 $Boxplot$ of Y_1 and identified parameters $x_1..x_i$ of the process of obtaining breathing air for $n = 62$ observations of the measurement data series. Source: own research.

The result of $U\ Mann-Whitney$ test confirmed the existing difference of the analysed groups for the „good" $\eta_1 = 496{,}5ppm$ and „bad" product $\eta_2 = 588ppm$. The computed test statistic $W = 790$ with the value $p-value = 0 < 0{,}05$ suggests rejecting the H_0 and adopting the alternative hypothesis $H_1: \eta_1 \neq \eta_2$ confirming a significant difference in the medians of the analysed product groups. This confirms the influence of the analysed parameter on the process under consideration, Fig. 6-9. The $U\ Mann-Whitney$ test is weaker than $t-Student's$ test, hence greater caution should be exercised in interpreting the results obtained. At the stage of verifying the test applicability assumptions, the homogenity of the variances[36] was tested by verifying the hypothesis $H_0: \sigma_1 = \sigma_2$ against the alternative $H_1: \sigma_1 \neq \sigma_2$ at the significance level of $\alpha = 0{,}05$. For the $Levene's$[37]test the $p-value = 0{,}744$ indicates that the result is not statistically significant and no basis for was found for the rejection of H_0 and therefore accepting the assumption of homogeneity of the analysed variances. Despite the lack of normality of the analysed distributions[38] conclusions stemming from $U\ Mann-Whitney$ test were alternatively confirmed with $t-Student's$ test for $n = 2$ independent groups estimating a power of inference at the level of $1-\beta = 0{,}994$ for sample $n = 28$ and an identified difference in mean values of $\bar{x}_1 - \bar{x}_2 = 62{,}5ppm$. The hypothesis: $H_0: \bar{x}_1 = \bar{x}_2$, was verified in relation to the alternative: $H_1: \bar{x}_1 \neq \bar{x}_2$ for the significance level of α 0,05. The calculated value of the test statistic amounted to $t = -4{,}21$. Because of the calculated value $p-value = 0 < 0{,}05$ the tested hypothesis H_0 should be rejected in favour of the alternative hypothesis H_1 assuming that the mean values are significantly different from one another.







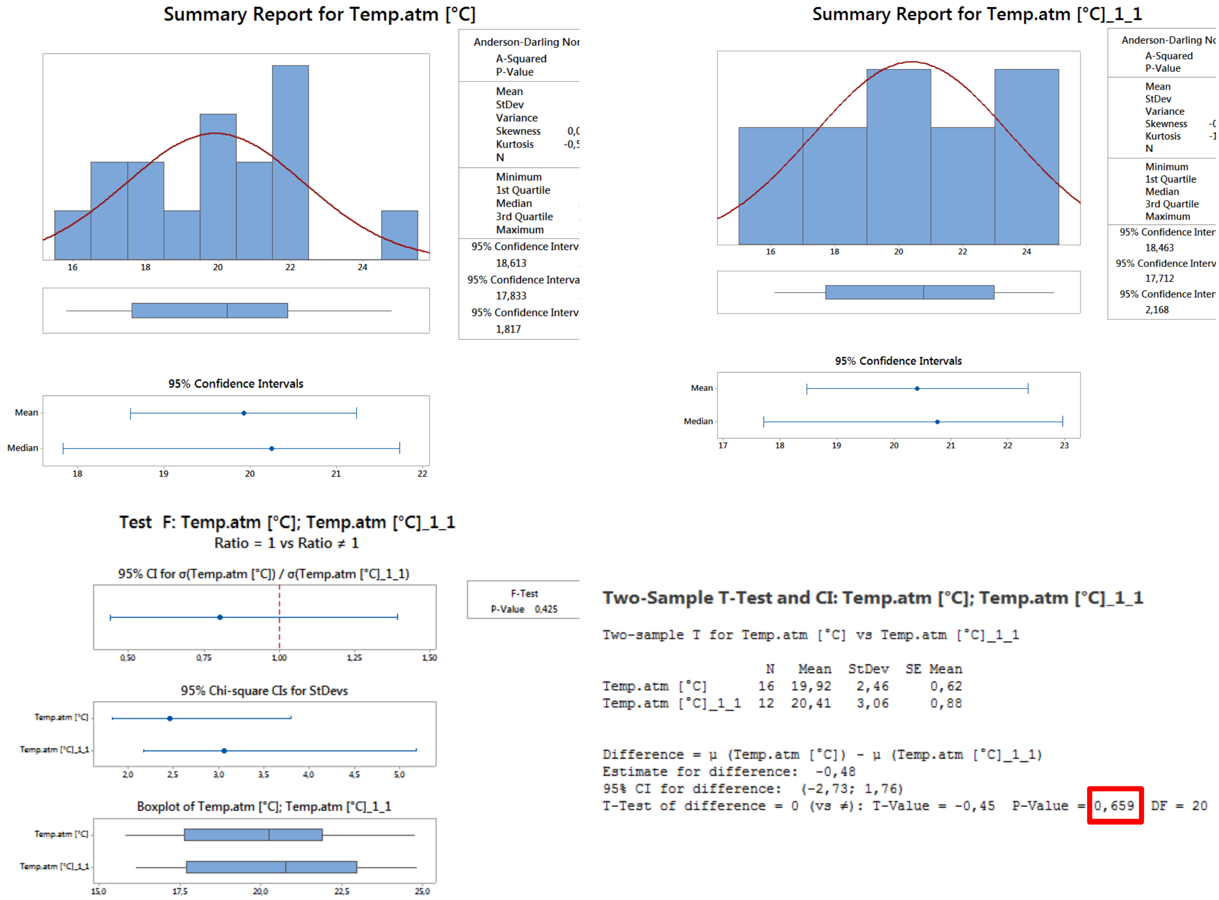


Mann-Whitney Test and CI: CO2 atm [ppm]; CO2 atm [ppm]_1

```
                 N  Median
CO2 atm [ppm]    34  496,50
CO2 atm [ppm]_1  28  588,00


Point estimate for η1 - η2 is -71,61
95,2 Percent CI for η1 - η2 is (-99,01;-34,00)
W = 790,0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0,0001
The test is significant at 0,0001 (adjusted for ties)
          Two-sample T for CO2 atm [ppm] vs CO2 atm [ppm]_1

                                         SE
                       N   Mean  StDev  Mean
          CO2 atm [ppm]    34  513,2   58,7    10
          CO2 atm [ppm]_1  28  575,7   57,5    11


          Difference = μ (CO2 atm [ppm]) - μ (CO2 atm [ppm]_1)
          Estimate for difference:  -62,5
          95% CI for difference:  (-92,2; -32,9)
          T-Test of difference = 0 (vs ≠): T-Value = -4,21  P-Value = 0,000  DF
          Both use Pooled StDev = 58,1578
```

Fig. 6-9 Testing of the normality of distributions of the empirical data series for the two groups of products *Good v. Bad* CO_2 along with parametric $t-Student's$ test and non-parametric $U\ Mann-Whitney$ test. Source: own research.

Consequently, the $t-Student's$ test for the next parameter was used to verify the difference in the observed values of the mean temperature distributions $\bar{x}_1 - \bar{x}_2 = 20{,}41 - 19{,}92 = 0{,}49^0C$ in both process states, testing the hypothesis: $H_0: \bar{x}_1 = \bar{x}_2$, against the alternative: $H_1: \bar{x}_1 \neq \bar{x}_2$. For the adopted significance level of $\alpha = 0{,}05$, the obtained value $p - value = 0659 > 0{,}05$ suggests the adoption of the tested hypothesis H_0 and rejection of the alternative hypothesis H_1. Thus, the impliccation is that there is insufficient indication of a statistically significant difference in the analysed parameter for *good* and *bad* product. It can therefore be assumed that temperature does not affect the process response. These conclusions require to be approached with caution due to the small sample size and the variability of the observed temperature[39] in the compared distributions of the empirical data series. Given the impossibility of forcing larger differences in temperature settings, this parameter was left for further observation. In order to obtain an unambiguous answer, the inference should be continued after obtaining the varied supplementary data of the analysed parameter, fig.10-13.



Two-Sample T-Test and CI: Temp.atm [°C]; Temp.atm [°C]_1_1

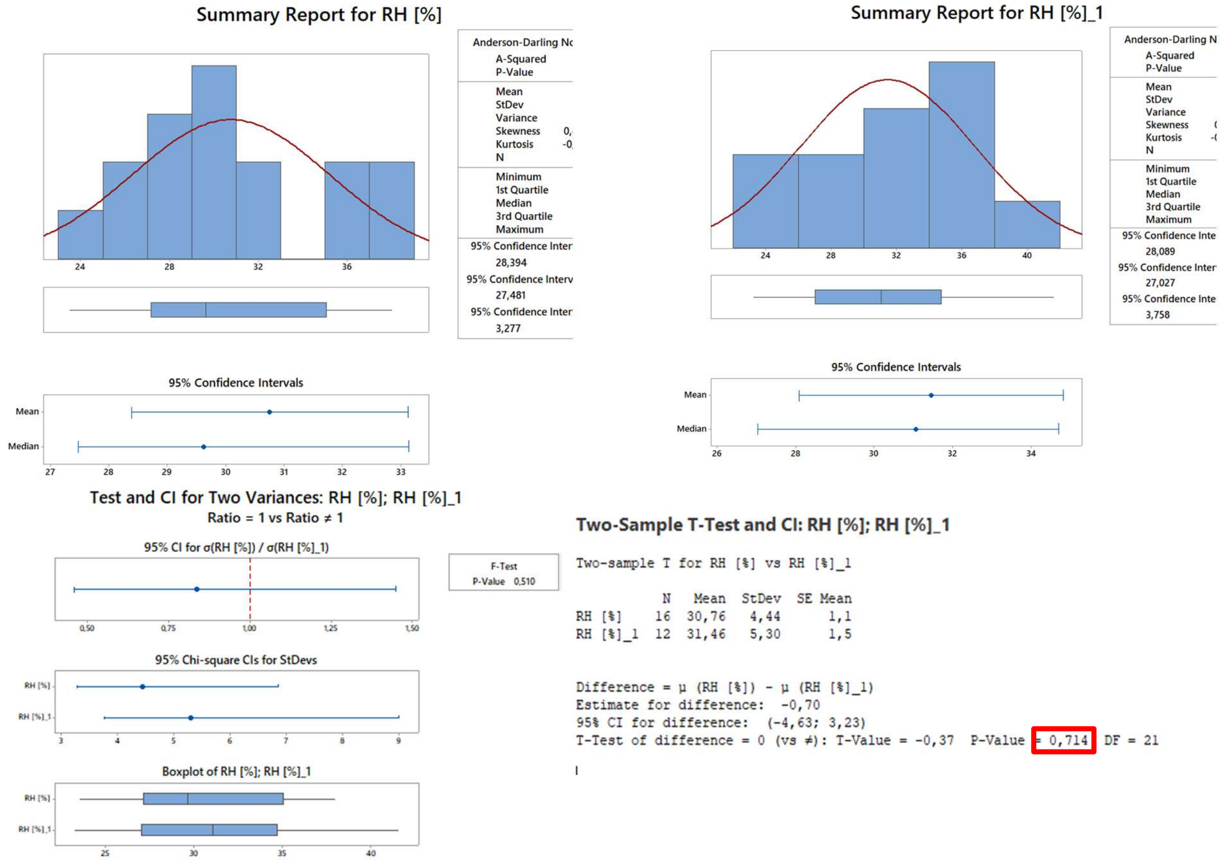
```
Two-sample T for Temp.atm [°C] vs Temp.atm [°C]_1_1

               N   Mean  StDev  SE Mean
Temp.atm [°C]      16  19,92   2,46     0,62
Temp.atm [°C]_1_1  12  20,41   3,06     0,88


Difference = μ (Temp.atm [°C]) - μ (Temp.atm [°C]_1_1)
Estimate for difference:  -0,48
95% CI for difference:  (-2,73; 1,76)
T-Test of difference = 0 (vs ≠): T-Value = -0,45  P-Value = 0,659  DF = 20
```

Fig. 10-13 Testing of the normality of distributions of empirical data for two temperaturę groups for *Good v. Bad* product along with $F-test$ for homogeneity of variance and a comparison of the mean values of the distributions of $\bar{x}$ temperature T using the $t-Student's$ test. Source: own research.

In the next step, an analogous hypothesis testing was performed for the identified differences in the mean values of atmospheric relative humidity, fig.14-16. The homogeneity of the variances was compared by verifying the hypothesis $H_0: \sigma_1 = \sigma_2$ against the alternative $H_1: \sigma_1 \neq \sigma_2$ at the significance level of $\alpha = 0{,}05$. The $p - value$ =0,510 for the $F - test$ indicates no basis for rejecting H_0, thus the variances are equal. Using the $t - Student's$ test the mean values of the humidity distributions $\bar{x}_1 - \bar{x}_2 = 31{,}46 - 30{,}76 = 0{,}7\%$ were compared and verified for both process states by testing the hypothesis: $H_0: \bar{x}_1 = \bar{x}_2$, against the alternative: $H_1: \bar{x}_1 \neq \bar{x}_2$. The resulting $p - value = 0{,}714$ is in favour of hypothesis H_0 for the adopted significance level of $\alpha = 0{,}05$. Hence, for the "good" and "bad" product, differences in mean values cannot be conclusively confirmed and the parameter under consideration does not affect the process response. As before, these conclusions should be approached with caution. With the exception of the significant impact of atmospheric carbon dioxide concentration $x_1 - C_{CO_2 a}$ the impact of $x_4 - RH[\%]$ and temperature changes $x_2 - T_a$ on the process response was not confirmed.

Statistical hypothesis testing was complemented by an analysis of the significance of the correlation between operating time t_{pr} and carbon dioxide content C_{CO_2} downstream of the filtration system, fig.17-18. The graph indicates that the loss of sorption properties occurs quite rapidly as a function of bed operating time. The calculated Pearson linear correlation coefficient amounted to $r = 0{,}707$, $p - value = 0{,}033$ where $r^2 =$

$0{,}499 \approx 0{,}5$. The calculated test statistic value $t = \frac{|r|\sqrt{n-2}}{\sqrt{1-r^2}} \approx 2{,}64$ is greater than the critical value for the two-sided test $t_{kr} = 2{,}36$ for $\alpha = 0{,}05$ and $n = 9 - 2 = 7$ degrees of freedom [9]. Consequently, the tested null hypothesis $H_0\!: \rho = 0$ (no linear correlation between bed operation time and carbon dioxide content) should be rejected in favour of the alternative $\mathrm{H}_1\!: \rho \neq 0$ (a significant correlation exists between the variables) [10].



Two-Sample T-Test and CI: RH [%]; RH [%]_1

```
Two-sample T for RH [%] vs RH [%]_1

           N   Mean  StDev  SE Mean
RH [%]    16  30,76   4,44      1,1
RH [%]_1  12  31,46   5,30      1,5


Difference = µ (RH [%]) - µ (RH [%]_1)
Estimate for difference:  -0,70
95% CI for difference:  (-4,63; 3,23)
T-Test of difference = 0 (vs ≠): T-Value = -0,37  P-Value = 0,714  DF = 21
```

Fig. 14-16 Testing of the normality of product group distributions along with the $F - test$ on homogeinity of variance and comparison of the mean values of relative humidity $\bar{x}$ distributions using the t$-Student's$ test for *Good v. Bad* groups of products. Source: own research.

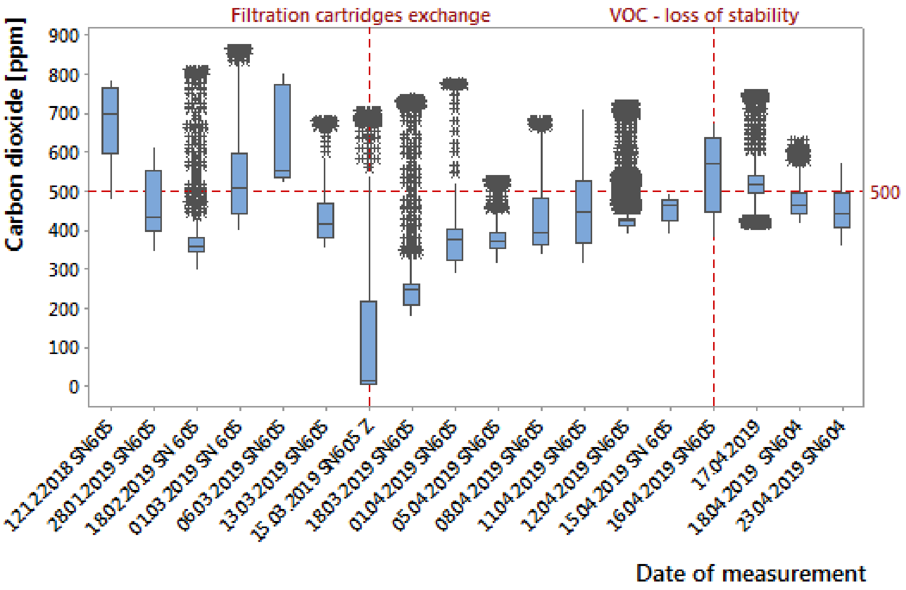


Fig.17 CO_2 measurement variability in time in the process of production of breathing air. Source: own research.

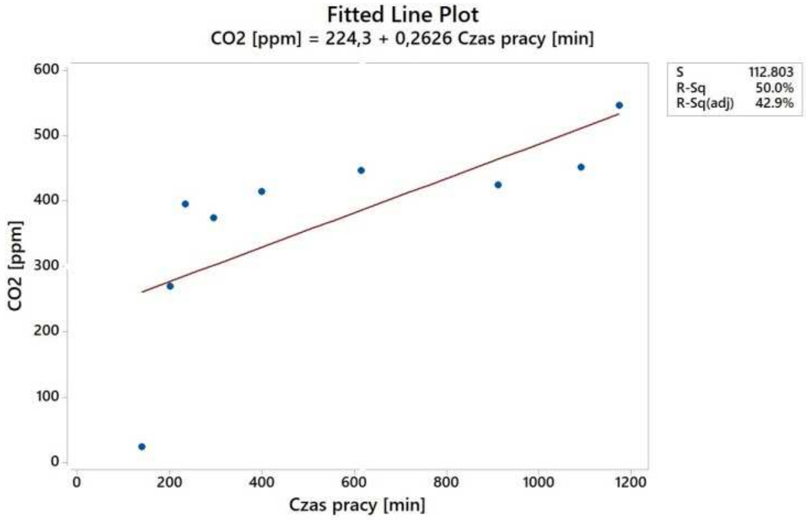


Fig. 18 Correlation plot of CO_2 content in the product against the operation time of the filtration system after filter cartridge replacement from 15.03.2019.to 16.04.2019. Source: own research.

Comparative analysis of the data series distributions confirmed that environmental exceedances of carbon dioxide $x_1 - C_{CO_2\,a}$ in the substrate, have a significant impact on the defined $CTQs\ (Y_1, Y_2)$, tab.5.

Tab. 5

Summary of inference results for key process parameters. Source: own research.

No.	*Parameter*	*Hypothesis*	*p-value*	*Result*	*Conclusions*
1	$x_1 - C_{co_2\,a}\,[ppm]$	$H_0{:}\ \bar{x}_{Di} = \bar{x}_{Zi}$ $H_1{:}\ \bar{x}_{Di} \neq \bar{x}_{Zi}$	*0,0001*	*negative*	$With\ \alpha = 0{,}05$, $C_{co_2\,a}$ affects Y_1
2	$x_2 - T_a[C^0]$		*0,659*	*positive*	$With\ \alpha = 0{,}05$, T_a does not affect Y_1. Contrary to theoretical considerations - low coefficient of variation $V_{1-2} = \frac{S}{\bar{x}}$ 3,08 and 4,33 $< 10\%\ for\ n < 15$
3	$x_4 - RH[\%]$		*0,714*	*positive*	$With\ \alpha = 0{,}05$, RH does not affect Y_1 Low coefficient of variation $V < 10\%$ dla $n < 15$
4	$x_7 - t_{pr} = f(m_s)$	$H_0 = 0$ $H_1 \neq 0$	*0,033*	*negative*	$With\ \alpha = 0{,}05$ *A strong statistically significant correlation exists between the parameters. An increase in* t_{pr} results in an increase in the output parameter $Y_1 = C_{CO_2}$

On the basis of the empirical data series obtained, it was conclusively confirmed that, inter alia, an excessive CO_2 content in the substrate influences the breakthrough time of the filter bed and thus the proportion of the observed defects in the production process. During the study, the observed concentration of carbon dioxide in the air intake atmosphere was C_{CO_2} a $\in [382 \div 1042]$ppm., fig. 19.

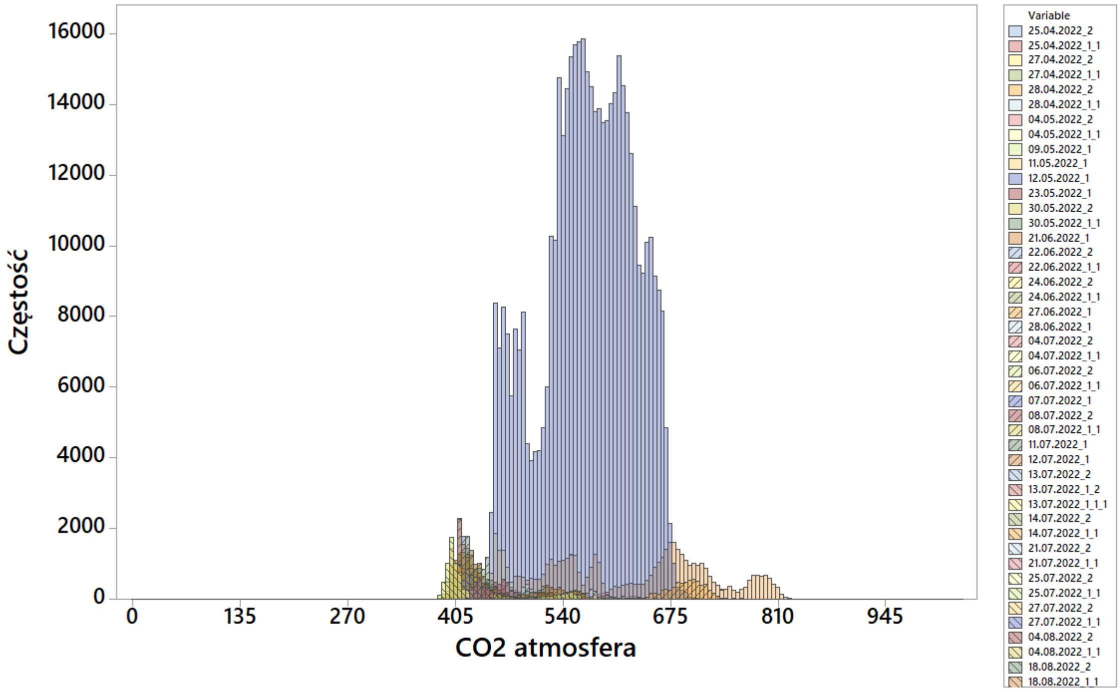


Fig. 19 Distribution of empirical data of carbon dioxide concentration in the atmosphere of the compression and filtration system intake. Source: own research.

The results of the study[40] allowed the identification of significant parameter effects[41] on the process response. It confirmed that Y_1, Y_2 after eliminating insignificant model parameters are correlated with more than one factor. Accordingly, the process response was obtained with $Y_1 < 500ppm = f(x_1, x_2, x_7)$. As a result of the study, the significant influence of: substrate impurities x_1 on the purification capacity of the analysed breathing air treatment system and its operating time x_7 was confirmed. It is indisputable that the configuration of the filter bed used x_6 and the operator x_5 have an impact on the operating time of the system x_7. The final result may be expressed as $Y_1 = f(x_1, x_2, x_5, x_6)$. Once the relevant process setting had been determined, the improvement areas (so-called Focus Areas) initially defined on the basis of the $FMEA$ analysis were refined, tab.5 and a decision was taken to implement corrective changes [5].

Given the limited possibilities to influence the control of carbon dioxide content in the substrate[42] an attempt was made to modify the sorption processes in order to increase the robustness of the filtration systems and reduce the Y_1 values. The possibility of using a new type of filter bed x_6 was explored. This required a technological leap and a separate project task to design a new product[43] for an existing process within the $DFSS$ apprach[44]. Overcoming the technological barriers was necessary due to reaching the ceiling of the capabilities of the originally analysed filtration process based on standard sorbent beds configured by manufacturers. Modification of the filtration system bed in the process of obtaining, maintaining and distributing breathing air intended for oxygen hyperbaric conditions for$DGKN - 120$ was carried out at $KTPP\ AMW$. It was concluded that the cumulative effect of activities in the specified improvement areas $no. 1-4$ could result in achieving a minimisation of the share of observed process defects to the defined level of $\overline{Y_1} \leq 5\%$, tab. 6.

Tab. 6

Focus Area for the rationalisation of the process of obtaining breathing air. Source: own elaboration.

No.	*CTQ*	*Parameter*	*Process modification*
1	$Y_1 = C_{CO_2} \leq 500[ppm]$	x_5 −operator	training and modification of SOP
2		$x_1 - C_{CO_2\,a}\,[ppm]$	$C_{CO_2\,a} < 500ppm$ in atmospheric air at the compressor intake
3	$Y_2 - t_p \geq 3msc.$ $t_p \geq 50\ godz.$	$x_2 - T_a[C^0]$	$T_a \in [15-25]^0C$ temperature of atmospheric air at compressor inlet
4		$x_6 - m_s -$ filter bed filling configuration	technology change-modification of the sorption processes for compression and filtration system failure-free operation time consisting in meeting Y_1, Y_2.

In the first phase of the activities, the simplest changes consisting of changing the $SOPs$ and training of operators x_5 in combination with the implementation of online product quality control and the provision of a possible reduction in the carbon dioxide content in the substrate x_1. These measures resulted in a reduction in the proportion of observed defects in the distribution of the empirical data series from $\bar{Y_1} \approx 10{,}17\%$, fig. 20 to $\bar{Y_1} \approx 0\%$, fig.21 and 22. The resulting change in process alignment was not fully satisfactory, the distribution of the data series measuring the carbon dioxide content of the product was close to USL[45]. The next step was to implement technology changes for the chemisorption processes x_6, with the essence of the solution not presented here as it will be described separately. This resulted in a level close to the ceiling of expected capabilities moving away by $Z = \frac{x_{USL}-\bar{x}}{\sigma}$ where: x_{USL}- upper specification limit; $\bar{x}$ −arithmetic mean; σ −standard deviation: $Z_{bench\ USL} = 11{,}59$ from the established upper specification limit $USL = 500ppm$ approaching permanently from the level initially observed: $\bar{x}_{1-1} = 441ppm\,(x_{CO_2 max} = 588ppm46), \sigma = 37{,}32ppm$ fig.20, through $\bar{x}_{1-2} = 379ppm\ (x_{CO_2 max} = 499ppm)$ and $\sigma = 21{,}02ppm$ fig.21[47] to the average value of $\bar{x}_{1-3} \approx 33ppm$ with $\sigma = 0{,}84ppm$[48], fig.23. The observed change in the distribution parameters indicates the key influence of the modification of the filter bed and a significant improvement in the process[49], both in terms of its position relative to the tolerance limits and the observed variability. Complete elimination of the occurrence of defects, a significant shift of the distribution away from the upper tolerance limit and low variability indicates a regaining of control over the process and its controllability. As a consequence of the changes in the carbon dioxide elimination technology, significant improvements were made in the capacity[50] and stability of the process over time, which is, inter alia, a function of the modification of the bed and the input content of carbon dioxide in atmospheric air. The qualitative modification of the bed resulted in a reduction of the output parameter $Y_1 \ll 500ppm$ o and extended the time of protective operation of the filtration system to a total time of $Y_2\,(t_p) = 123{,}30\ h \gg LSL = 50\ h$, i.e. 2.5 timeslonger than the normatively required minimum time of failure-ree operation of the compression system. The modification of the filtration process in comparison with the original technical solution allowed the use of a new filter beds $ALFA\_01$ for the time of $t_{p-2} = 123{,}30h$ fig. 24 and $ALFA\_02$ for the time of $t_{p-2} = 158h$ fig. 27.

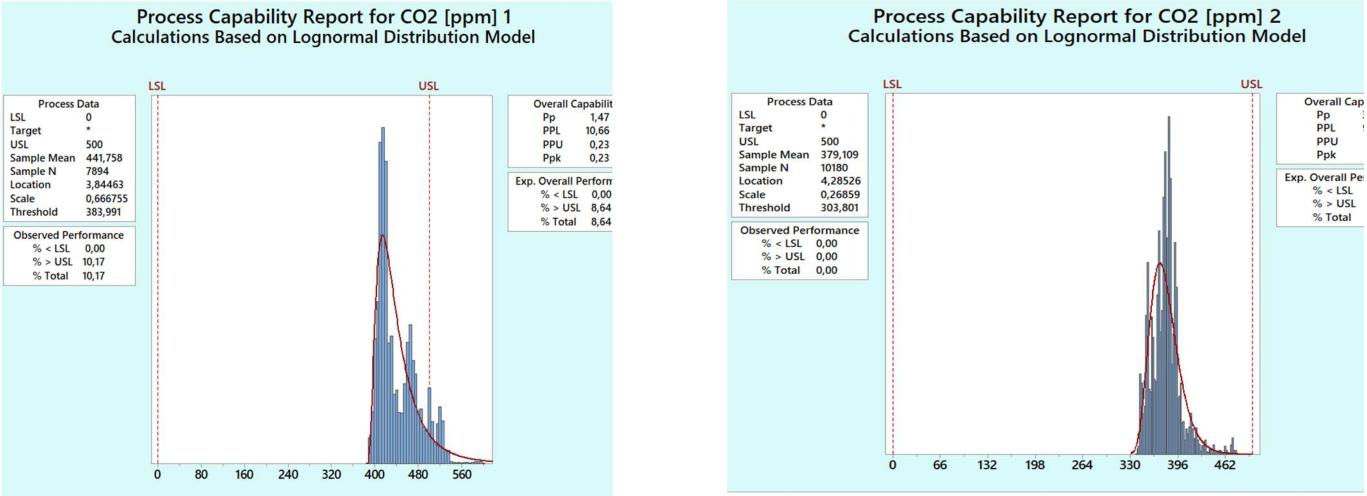


Fig. 20-21. Variation of CO_2 parameters over time for the breathing air production process: before 25.11.2019 and after process modification on 31.02.2020 consisting in the modification of parameter x_1 – reduction of carbon dioxide content in the substrate within the temperature limits x_2 and SOP training of operators x_5. Source: own research.

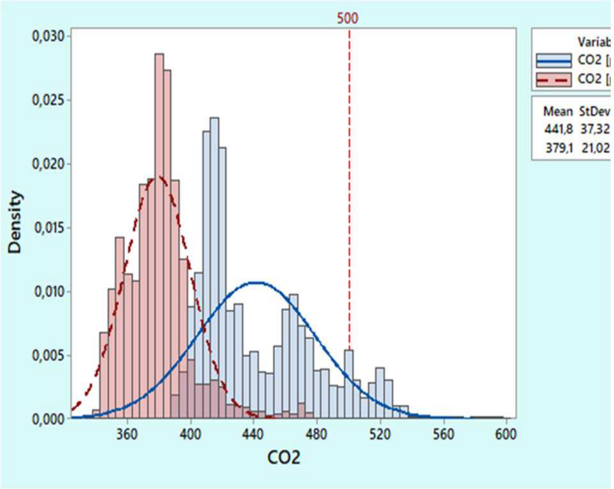
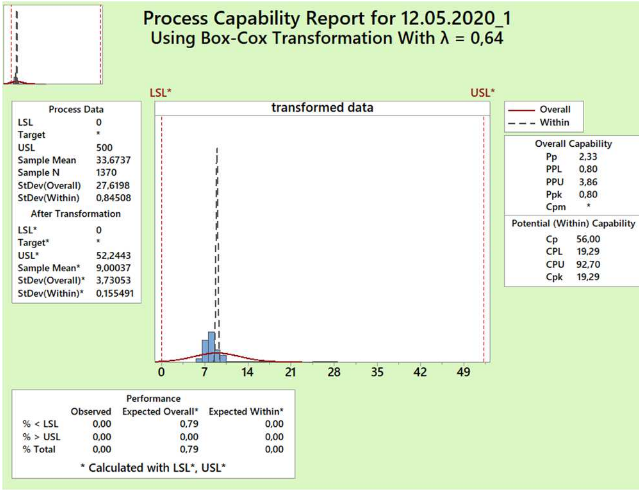


Fig. 22 CO_2 measurements distribution before and after process change consisting in the modification of x_1 – reducing carbon dioxide in the substrate within temperature ranges of x_2 and SOP operator training x_5. Source: own research.



Process Data

LSL	0
Target	*
USL	500
Sample Mean	33,6737
Sample N	1370
StDev(Overall)	27,6198
StDev(Within)	0,84508
After Transformation	
LSL*	0
Target*	*
USL*	52,2443
Sample Mean*	9,00037
StDev(Overall)*	3,73053
StDev(Within)*	0,155491

Overall Capability

Pp	2,33
PPL	0,80
PPU	3,86
Ppk	0,80
Cpm	*

Potential (Within) Capability

Cp	56,00
CPL	19,29
CPU	92,70
Cpk	19,29

Performance

	Observed	Expected Overall*	Expected Within*
% < LSL	0,00	0,79	0,00
% > USL	0,00	0,00	0,00
% Total	0,00	0,79	0,00

* Calculated with LSL*, USL*

Fig. 23 Variation of CO_2 measurements in time in the breathing air production process: before 31.02.2020 and after process modification on 12.05.2020 consisting in filter bed modification x_6.. Source: own research.

Under the critical conditions of carrying out underwater work[51] in the atmospheric environment of the compression and filtration system intakes contaminated with excessive amounts of carbon dioxide, this allows the carbon dioxide content downstream of the filtration system to be reduced to as low as $C_{CO_2} \leq 10ppm$. In accordance with the operating procedure hitherto in use, once the sorption properties have been lost, the entire set of filter media should be replaced and the used elements disposed of, i.e. as observed already after $Y_2 = 19{,}30$h. The distributions of changes in the concentration of carbon dioxide downstream of the filtration system after the implementation of process changes and filter media modifications in time are presented in fig. 24-25.

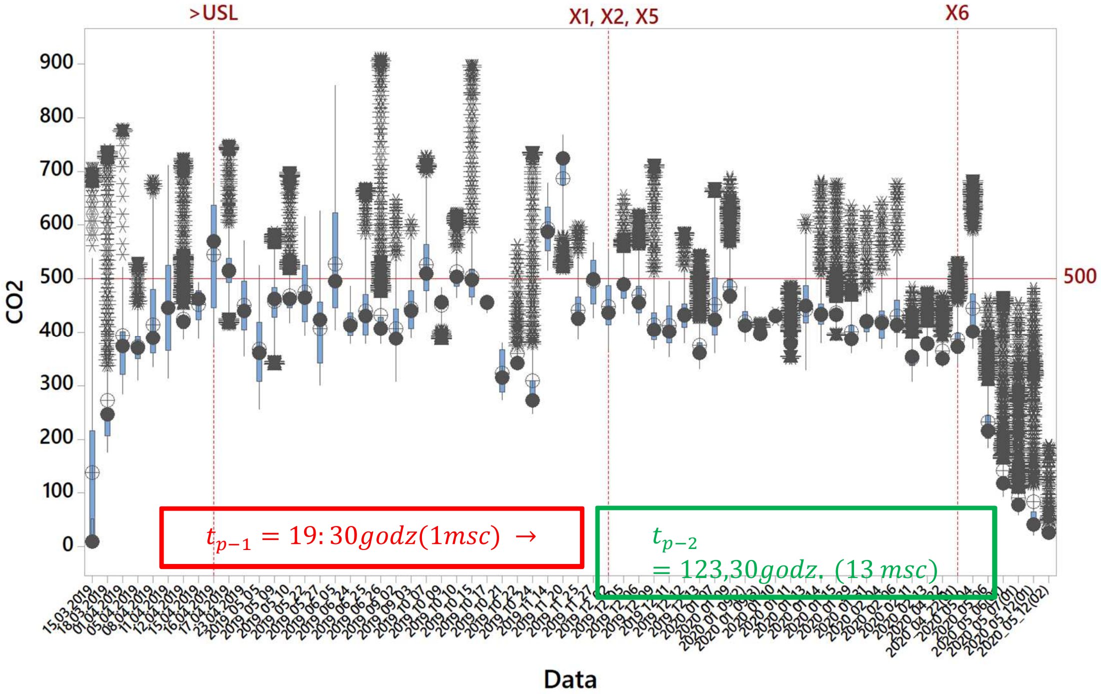


Fig. 24 Variation over time of CO_2 measurements in the breathing air production process following the implementation of process modification and filtration bed replacement with $ALFA_{01}$. Source: own research.

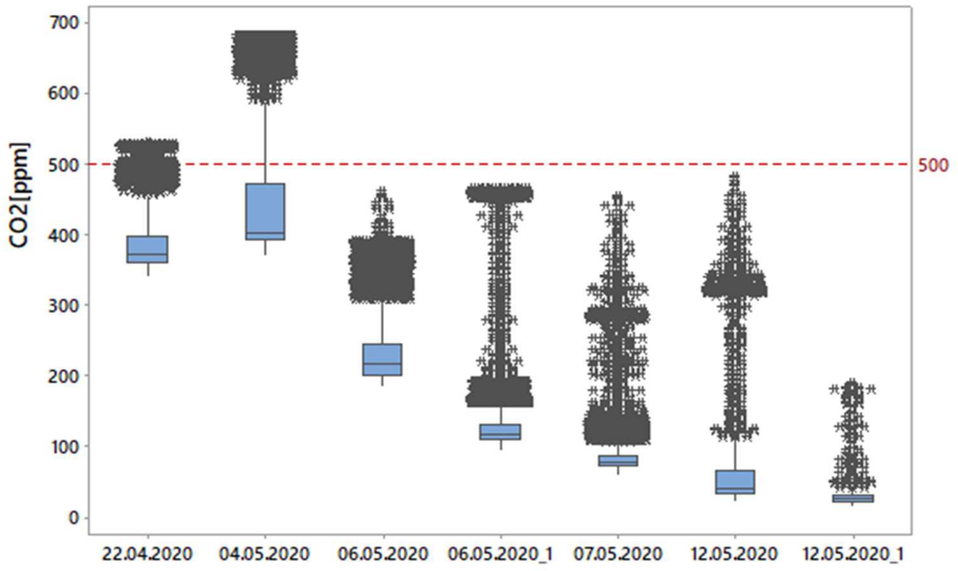


Fig. 25 Variation over time of CO_2 measurements in the breathing air production process following the implementation of process modification and filtration bed replacement with $ALFA_{01}$.Source: own research.

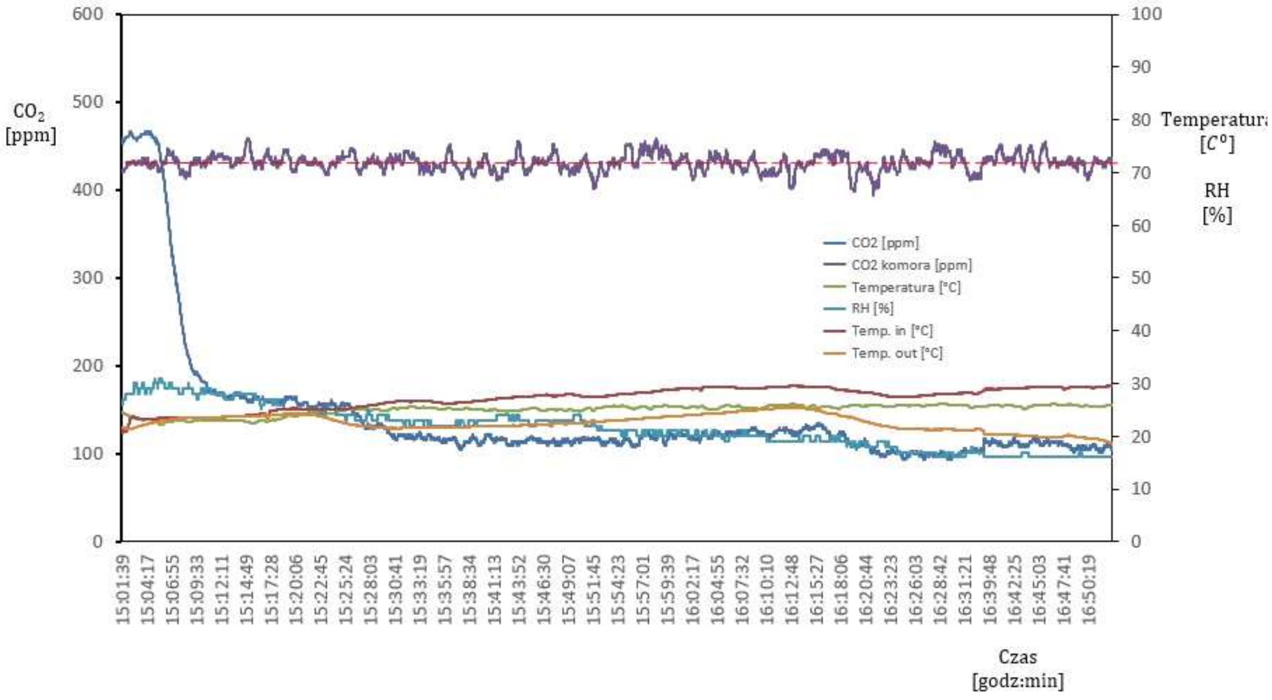


Fig. 26 Variation over time of CO_2 measurements for the selected distribution as at 06.05.2020 after the implementation of process modification and filtration bed replacement with $ALFA_{01}$.Source: own research.

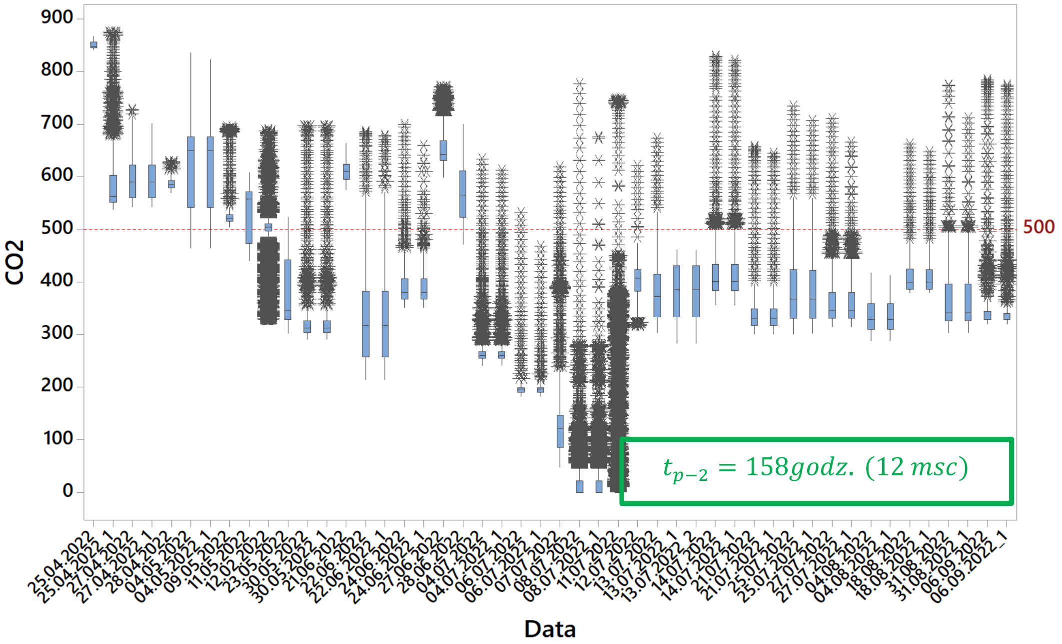


Fig.27. CO_2 content in the breathing air downstream of the filtration system: $S\&S\,WP4341$, $SECCANT\ IIIA$, $BAUER\ P140$ following the implementation of technology changes and filter bed modification x_6. Bed operational time $Y_2 = 158\text{hours} \gg 50$ hours for $ALFA\_02$ filter bed. Source: own research.

At the control stage, all data during the performance tests were consistently monitored, recorded and observed. Empirical data distributions were plotted on the basis of individual measurement data series obtained before and after the process modification. The effects of the modifications lead to the conclusion that the robustness of the system to changing environmental conditions has improved significantly and the process rationalisation has brought the desired effect. Despite the high content of carbon dioxide in the ambient air (at the inlet to the compression system), the results of the control measurements confirmed the minimal concentration of CO_2 impurities in the product batch fig. 26. The breathing air filtration system and therefore the product is much less sensitive to high CO_2 content in the substrate[52].The high quality of the breathing air after the process modification is confirmed by the results of in-service testing of the carbon dioxide content of the control samples obtained using an automated indicator measuring system for online control[53] and analytical laboratory tests performed at the independent physico-chemical breathing gas laboratory $WTM1RBlog$, test protocols no. 118 and 128/2020, tab. 8[54].Consequently, overcoming environmental constraints and increasing system resilience as a result of the implemented measures in the defined areas of improvement resulted in a significant rationalisation of the process and the achievement of the defined CTQ requirements, tab. 7. In practice, the effective time of active operation of the filter set bed at a pressure of $p = 30MPa$ may vary, as it depends, inter alia, on: bed mass x_6, adherence to $SOP\ x_5$, carbon dioxide content in the substrate x_1[55] and temperature x_2[56].

Tab. 7

Comparison of the observed process capability before and after modification of the breathing air technology. Source: own elaboration.

CTQ	Target	Process capacity	
		Before	After
$Y_1 = C_{co_2} \leq 500[ppm]$	$5\% > USL$ $C_p, C_{pk} \geq 1$	$17{,}74\% > USL$ $C_p, C_{pk} \cong min[0{,}86; 0{,}51]$ $P_p, P_{pk} \cong min[0{,}63; 0{,}37]$	$0\% > USL$ $C_p, C_{pk} \cong min[56; 19{,}29]$ $P_p, P_{pk} \cong min[2{,}33; 0{,}80]$
$Y_2 - t_p \geq 3months$ $t_p \geq 50\ h$	$10\% < LSL$ $C_p, C_{pk} \geq 1$	$100\% < USL$ $t = 19h30\ min < 50h$	$100\% > USL$ $t = 123h30\ min > 50h$

Tab. 8

Results of laboratory tests of breathing air quality following process modification according to NO-07-A005:2010. source: own elaboration on the basis of protocols drawn up by $WTM1RBlog$ No. 118 and 128/2020.

Parameter	Before	After modification
	acc. to NO—07—A005:2010 Protocol no. 118/2020 as at 04.05.2020 WP4341 SN112605	wg.NO—07—A005:2010 Protocol no. 128/2020 as at 07.05.2020 WP4341 SN112605
$C_{CO_2}[\%]v/v$	0,0327	**0,0059**
$C_{H_2O}[mg \cdot m^{-3}]$	25,90	20,57
Total hydrocarbons converted to CH4 $[mg \cdot m^{-3}]$	1,06	1,14
C_{CO}[ppm]	0	0
$C_{O_2}[\%]v/v$	20,74	21
C_{NO_x}[ppm]	0,04	0,04

The elimination of excessive CO_2 from the breathing air batch was not accompanied by an increase in other standardized critical respiratory air pollutants.

CONCLUSIONS

Achieving the objective of the work in terms of reducing the number of defects caused by an excessive CO_2 content in the process of obtaining breathing air for hyperbaric oxygen conditions was realised by rationalising the process by implementing corrective actions in the identified areas of improvement. The minimisation of process defects led to a reduction in financial outlays resulting from revealed internal and external costs of poor quality while achieving an adequate ROI [57]. Reductions in financial outlays resulting from the costs of poor quality processes in the responsible hyperbaric breathing air distribution systems were accompanied by significant improvements in the capacity[58] and stability of the production process over time and a reduction in unplanned operational shutdowns of the compression and filtration systems (improved OEE)[59]. The process correction allowed the previously revealed technological barriers of the filtration systems to be overcome due to reaching the ceiling of their capabilities. Modification of the filtration process, training of operators and development of new $SOPs$/OCAPs[60] together with the implementation of qualified, reliable and useful automated indicative measurement systems[61] (*online* quality control) minimised the share of observed process faults to a level below the defined correction target, i.e. $\overline{Y_1} = 0 \leq 5\%$ [11,12].

Under current operating conditions, control of a highly variable production process is not possible without reliable and useful measurements and periodic laboratory control (every 3÷6 months) cannot be the basis for full detection and correct inference about the state of the process during the control interval. The obtained results confirmed the positive impact of the activities on meeting the defined critical requirements CTQ both in terms of the required carbon dioxide content of the control sample Y_1 and the operation time of the bed Y_2. Following the process modification, a significant increase in the operating time of the compression and filtration systems was achieved relative to the originally observed bed breakthrough time of $Y_2 = 19{,}30\text{h} \ll 50\,h < \text{LSL}$ accompanied by the maintenance of CO_2 content in the product at the normatively required level of $C_{CO_2} < 500ppm$. Thereby, an almost 2.5 times longer failure-free operation time of $t_{pr} = 123{,}30\,h$, was ensured as compared to the normatively required $t_{pr} > 50h$, and about 6 times longer than originally observed before the rationalisation $Y_2 = 19{,}30\text{h} \ll 123{,}30h$. During the study, after applying further modifications to the bed, this time was extended to $t_{pr} = 158h$. An extension of the filter cartridge change intervals has thus been achieved[62], even where excessive[63] carbon dioxide contamination of the atmospheric air cannot be effectively eliminated. The resistance of the process to interference due to the occurrence of special causes has been improved.

Conclusions from the analysis of the applied technical solution related to the modification of the$SWOT/TOWS$[64,65]manufacturing technology indicate the dominance of strengths over weaknesses, which appear to be compensable within the $MGPP$ approach[66]. Further follow-up work offers the opportunity to search for the field of optimal process response[67] using classical experiment design methods. At the moment, the improvements achieved and the recovery of control over the process with the implementation of proper monitoring permits the production of large batches of high quality breathing air for hyperbaric purposes. This ensures enhanced safety for diving and the performance of underwater work by minimising the toxicological risks for divers especially in hyperbaric conditions.

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[2] Experimental Deep-water Hyperbaric System
[2] Doświadczalny Głębokowodny System Hiperbaryczny

[3] Carbon dioxide (IV)
[3] tlenek węgla (IV)

[4] CTQ - $Critical\ to\ Quality$
[4] ang. CTQ - $Critical\ to\ Quality$

[5] $n = 62$ successive distributions of historical data
[5] $n = 62$ kolejnych rozkładów danych historycznych

[6] for a single distribution as many as 65.5% defects were revealed for the worst-case criterion, where: $P_p, P_{pk} = [0{,}93; -0{,}26] min < 1$
[6] dla pojedynczego rozkładu ujawniono dla kryterium najgorszych okoliczności aż 65,5% wad, gdzie: $P_p, P_{pk} = [0{,}93; -0{,}26] min < 1$

[7] manufacturer declaration $t_p \approx$378 hours
[7] deklaracja producenta $t_p \approx$378 godzin

[8] Critical to Quality
[8] ang. Critical to Quality

[9] e.g. using the *Design for Six Sigma (DFSS)* approach. A method of designing a new product and/or process, or redesigning an existing one, where the process has reached a ceiling of its capabilities
[9] np. z wykorzystaniem podejścia $DFSS$ – ang. $Design\ for\ Six\ Sigma$. Metoda projektowania nowego produktu lub/i procesu lub przeprojektowania istniejącego, w przypadku, gdy proces uzyskał pułap swoich możliwości

[10] process capability indicators: $P_p = 6{,}92, P_{pk} = -35{,}18 \gg 1{,}33$
[10] wskaźniki zdolności procesu: $P_p = 6{,}92, P_{pk} = -35{,}18 \gg 1{,}33$

[11] external and internal
[11] wewnętrznych i zewnętrznych

[12] additional
[12] nadmiarowe

[13] Robust Design
[13] ang. Robust Design

[14] the adequacy of the filtration system selection declared by the selected manufacturers as appropriate for the limits of carbon dioxide content in ambient air at the level $C_{CO_2 a} = 0 \div 500ppm$
[14] deklarowana przez wybranych producentów adekwatność doboru systemu filtracji jest właściwa dla granic zawartości ditlenku węgla w powietrzu atmosferycznym na poziomie $C_{CO_2 a} = 0 \div 500ppm$

[15] Filter sets do not have the capacity to eliminate carbon dioxide above the content of $\mathrm{C}_{\mathrm{CO}_2 a}$ >500ppm and compression system with a capacity of $Q > 1000 dm^3/min$

[15] zestawy filtracyjne nie posiadają zdolności eliminacji ditlenku węgla powyżej zawartości $\mathrm{C}_{\mathrm{CO}_2 a}$ >500ppm i systemów sprężania o wydajności $Q > 1000 dm^3/min$

[16] revealed by periodic laboratory inspections

[16] ujawnionych w okresowej kontroli laboratoryjnej

[17] Failure Mode and Effect Analysis – the detailed descriptive part of the process risk analysis will not be provided here

[17] ang. Failure Mode and Effect Analysis - szczegółowa część opisowa analizy ryzyka procesu nie będzie tutaj przytaczana

[18] Standard Operational Procedures

[18] ang. Standard Operational Procedures

[19] Risk Priority Number

[19] ang. Risk Priority Number

[20] in-process measurement during batch production

[20] pomiar w trakcie trwania procesu na etapie wytwarzania partii wyrobu

[21] using gas chromatographic methods

[21] z wykorzystaniem metod chromatografii gazowej

[22] Maritime Technology Workshop of the 1st Regional Logistics Base in Gdynia

[22] Warsztaty Techniki Morskiej 1 Rejonowej Bazy Logistycznej w Gdyni

[23] $x_1 - CO_2$-carbon dioxide concentration in the ambient air at the compressor inlet, $x2$ – atmospheric air temperature at compressor inlet, $x_4 -$ relative humidity of the atmospheric air inlet to the compressor, $x_7 -$ operation time

[23] x_1 –stężenie ditlenku węgla CO_2 w powietrzu atmosferycznym na dolocie do sprężarki, x_2 –temperatura powietrza atmosferycznego na dolocie do sprężarki, x_4 –wilgotność względna powietrza atmosferycznego na dolocie do sprężarki, x_7 –czas pracy

[24] effect resulting from the correlation of one factor (parameter) with the setting of another factor(s)

[24] efekt wynikający z zależność jednego czynnika (parametru) od ustawień innego czynnika (czynników)

[25] which affect the process but cannot be controlled, e.g. operator behaviour, etc.

[25] które wpływają na proces, ale nie można ich kontrolować, np. zachowanie operatora itp.

[26] Mallows' *C(p)* statistic is an unconstrained estimator of the mean square of the prediction error in the population

[26] statystyka *C*(*p*) Mallows'a jest nieobciążonym estymatorem średniego kwadratu błędu przewidywania w populacji

[27] fulfilment of model assumptions

[27]spełnienia założeń modelu

[28] e.g. the inability to adjust the carbon dioxide content of the compression system's intake atmosphere

[28] np. brak możliwości nastaw zawartości ditlenku węgla w atmosferze czerpni systemu sprężania

[29] Design of Experiment

[29] ang. Design of Experiment

[30] an experiment in which tests were carried out for all possible combinations of factors and their levels of variation

[30] eksperyment, w którym przeprowadzono doświadczenia dla wszystkich możliwych kombinacjach czynników i ich poziomów zmienności

[31] where the process response met the CTQ requirements

[31] gdy odpowiedź procesu spełniała wymagania CTQ

[32] $n = 34$ of „good" distributions in relations to $n = 28$ of "bad" distributions"

[32] $n = 34$ rozkładów „dobrych" względem $n = 28$ rozkładów „złych"

[33] a non-parametric equivalent of the Student's t-test for independent samples

[33] nieparametryczny odpowiednik testu $t - Studenta$ dla prób niezależnych

[34] alternatively, it is possible to use $Mood's\ Median\ Test$

[34] alternatywnie można zastosować $Mood's\ Median\ Test$

[35] groups may have different variances that may not be detected

[35] grupy mogą mieć różne wariancje, które mogą nie zostać wykryte

[36] statistical equality of variance

[36] statystyczną równość wariancji

[37] it is not necessary for the series to have a normal distribution

[37] nie jest konieczne, aby serie podlegały rozkładowi normalnemu

[38] if there is no strong assymetry for $n > 15$ data in each group, it is worth considering the application of the $t -$ Student's test, as it produces a stronger result than non-parametric tests. Despite the fact that the distribution of the results of the dependent variable in each of the analysed groups does not follow a normal distribution, this test is quite robust to breaking this assumption

[38] jeżeli nie ma silnej asymetrii dla $n > 15$ danych w każdej grupie to warto rozważyć zastosowanie testu $t -$ Studenta gdyż, jest on mocniejszy od testów nieparametrycznych. Mimo tego, że rozkład wyników zmiennej zależnej w każdej z analizowanych grup nie podlega rozkładowi normalnemu, test ten jest dość odporny na złamanie tego założenia

[39] a low coefficient of variation $CV = RSD \cdot 100\% = \frac{s}{\bar{x}} \cdot 100\% = 3{,}08\% < 10\%$

[39] mały współczynnik zmienności $CV = RSD \cdot 100\% = \frac{s}{\bar{x}} \cdot 100\% = 3{,}08\% < 10\%$

[40] passive experiment

[40] eksperyment bierny

[41] controlled
[41] kontrolowanych

[42] this is not always possible in operational conditions
[42] nie zawsze jest to możliwe w warunkach eksploatacyjnych

[43] filter insert
[43] wkładu filtracyjnego

[44] systematised with a methodology to support the design or redesign of a new or existing product, service, process. Development of a new filtration medium and measurement system for online control of process parameters for obtaining breathing air for hyperbaric conditions.
[44] usystematyzowana metodyką wspierającą projektowanie lub przeprojektowanie nowego lub istniejącego produktu, usługi, procesu. Opracowanie nowego wkładu filtracji i systemu pomiarowego do kontroli $online$ parametrów procesu otrzymywania powietrza oddechowego na warunki hiperbaryczne

[45] USL – Upper Specification Limit
[45] ang. USL – Upper Specification Limit

[46] the observed momentary value after the compression system
[46] obserwowana wartość chwilowa za systemem sprężania

[47] following the change in SOP and the relative reduction in carbon dioxide content of the substrate
[47]po zmianie SOP i względnemu zmniejszeniu zawartości ditlenku węgla w substracie

[48] following implementation of the new filter bed
[48] po implementacji nowego złoża filtracyjnego

[49] especially after modification of sorption processes
[49] szczególnie po modyfikacji procesów sorpcji

[50] $C_p,\ C_{pk} = \min$ [56; 19,29]
[50] $C_p,\ C_{pk} = \min$ [56; 19,29]

[51] e.g rescue activities
[51] np. działania ratownicze

[52] in the atmosphere of the air intake of the compression system
[52] w atmosferze czerpni systemu sprężania

[53] recommended solution for compression and filtration systems operating in severe conditions
[53]rozwiązanie rekomendowane dla systemów sprężania i filtracji pracujących w ciężkich warunkach eksploatacyjnych

[54] the test was carried out after $9hours\ 41\ minutes$ of operation of the modified filter bed
[54] badania wykonano po $9godz\ 41\ min$ czasu pracy zmodyfikowanego złoża

[55] in confined spaces, e.g. requiring good ventilation
[55] w przestrzeniach zamkniętych. np. wymagających właściwej wentylacji

[56] left to observation
[56] pozostawiono do obserwacji

[57] ROI – Return of Investment
[57] ang. ROI – Return of Investment

[58] $C_p,\ C_{pk} = \min$ [56;19,29]
[58] $C_p,\ C_{pk} = \min$ [56;19,29]

[59] OEE – Overall Equipment Effectiveness – a measure of the efficiency of machinery and equipment. It measures the ratio of effective machine use time (output) to potential availability time (input)
[59] ang. OEE – Overall Equipment Effectiveness – wskaźnik miary efektywności maszyn i urządzeń. Określa stosunek czasu efektywnego wykorzystania maszyny (rezultat) do czasu potencjalnej dyspozycji (nakład)

[60] $OCAP$ – Out of Control Action Plan – plan for correcting the process in the event of non-compliance in order to achieve adequate performance
[60] ang. $\boldsymbol{OCAP}$ – Out of Control Action Plan. – plan korygowania procesu w przypadku wystąpienia niezgodności w celu uzyskania odpowiedniej wydajności

[61] the device was developed at KTPP AMW and validated under laboratory and real conditions supervising the production of breathing air supplied to the DGKN-120 system
[61] urządzenie opracowano w *KTPP AMW* i poddano walidacji w warunkach laboratoryjnych i rzeczywistych nadzorowania procesu produkcji powietrza oddechowego zasilającego system $DGKN-120$

[62] reducing the need for redundant replacement
[62] zmniejszając konieczność nadmiarowej wymiany

[63] $C_{CO_2a} > 500ppm$
[63] $C_{CO_2a} > 500ppm$

[64] $SWOT$ – (Strength – Weaknesses – Opportunities – Threaths)
[64] ang. $SWOT$ – (Strength – Weaknesses – Opportunities – Threaths)

[65] it will not be cited here as it is described separately
[65] nie będzie tutaj przytaczana , gdyż została odrębnie opisana

[66] $MGPP$ – Multi Generation Project Planning
[66] ang. $MGPP$ – Multi Generation Project Planning

[67] to develop the first series production unit of a new breathing air filtration system
[67] w celu opracowania pierwszego egzemplarza produkcji seryjnej nowego systemu filtracji powietrza oddechowego