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SIKORSKI W, SZYMCZAK C, SIODŁA K, POLAK F. Hilbert curve fractal antenna for detection and on-line monitoring of partial discharges in power transformers. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 343–351, http://dx.doi.org/10.17531/ein.2018.3.1.

This article describes the design of UHF Hilbert curve fractal antenna (HCFA) specially adapted for the partial discharge monitoring system. The authors present the mathematical apparatus for calculating resonant frequencies of Hilbert fractal antenna and results of a computer simulation of the developed prototype. In the design process, the antenna's working environment (mineral oil) and the mechantical construction of the transformer inspection window were taken into consideration as well. The article also shows the results of laboratory tests carried out in the transformer tank model with different type of partial discharge sources. Both simulations and partial discharge measurements showed that the HCFA, due to such properties as: multi-resonance, small size, low fabrication cost and high sensitivity, is an interesting alternative to other UHF probes installed in transformer inspection window.

## LEHRICH K, WĄSIK M, KOSMOL J. Identifying the causes of deterioration in the surface finish of a workpiece machined on a rail wheel lathe. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 352–358, http://dx.doi.org/10.17531/ein.2018.3.2.

Operational problems often remain undetected until a machine is commissioned and first machining is attempted. Heavy-duty machines are a specific group of machine tools due to the character of their manufacturing process. As they are often manufactured as single units, which involves high production costs, there are no prototype versions built and no tests are performed on them. Therefore, before the machine is complete, computer simulation methods are often the only validation tools of a machine project at the stage of designing. The variety of applications and the individuality of production are the reasons for the lack of standards defining the rigidity and precision of the cutting process performed by heavy machine tools. In this case analysis, the authors are considering a heavy duty rail wheel lathe, in which some issues were found during its exploitation which make it impossible to achieve the required shape, dimensions and surface finish, while working at set parameters. This article presents a comprehensive approach to the identification of the form and frequency of a machine tool supporting structure's self-vibrations and their potential sources in the case study of a horizontal lathe for railway wheelsets. The authors, drawing on the results of their long-standing research and their experience in the field of heavy machine tool design and testing, indicate self-excited vibrations as a key factor machine's operational behaviour, which is rarely considered in this type of machines.

## PROCHOWSKIL. Evaluation of the process of mileage growth during the operation of motor trucks, in several categories of engine cubic capacity. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 359–370, http://dx.doi.org/10.17531/ein.2018.3.3.

The intensity of use of motor vehicles and the range of the transport jobs performed change during the many-year operation of such vehicles. The changes are introduced in result of ongoing analyses of actual current vehicle operation costs, reliability, and performance characteristics. The changes in the vehicle operation process, taking place with vehicle's age, were analysed on the grounds of the mileage of over 9 000 motor trucks. The analysis covered a 20-year period of vehicle operation. The analysis results were used to estimate the mathematical models that describe the basic characteristics of the mileage growth process, with changes in these characteristics as observed in the recent years along with an intensive development of the road transport in Poland. Models of vehicle mileage growth have been developed for seven categories of engine cubic capacity. The coefficients of model equations have been given and the accuracy of the mileage values calculated on these grounds has been comprehensively evaluated. The relative measures of the scatter in the mileage values obtained from these models do not exceed 12 % of the average values determined from experimental data. A procedure has been proposed that leads to evaluating the mileage growth process and is based on the experience having already been gained in this field. It has been shown that the mileage growth process is strongly related to the engine cubic capacity. The mileage growth process is an important source of information for the planning of vehicle operation, forecasting of costs, and estimating of exhaust emissions and energy consumption in the whole cycle of operation of motor vehicles by transport companies.

#### WALISZYN A, ADAMKIEWICZ A. A method of vibration damping for diesel engine cylinder liners to prevent the consequences of erosion. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 371–377, http://dx.doi.org/10.17531/ein.2018.3.4.

This article presents the utilitarian need to determine the free vibrations of marine Diesel engine cylinder liners and the authors' own studies in this area. Theoretical investigations on free vibrations and experimental ones on forced vibrations have been described. Theoretical studies have been conducted with the application of characteristic dimensionless numbers in the Elektroniks Workbench and Wis Sim digital environment enabling virtual modeling of cylinder liner vibrations and determination

## SIKORSKI W, SZYMCZAK C, SIODŁAK, POLAK F. Antena fraktalna Hilberta do detekcji i monitoringu wyładowań niezupelnych w transformatorach energetycznych. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 343–351, http://dx.doi.org/10.17531/ein.2018.3.1.

W artykule zaprezentowano projekt anteny fraktalnej Hilberta przeznaczonej do stosowania w systemach monitoringu wyładowań niezupełnych wykorzystujących metodę UHF. Autorzy szczegółowo opisali aparat matematyczny służący do estymacji częstotliwości rezonansowych anteny fraktalnej Hilberta oraz wyniki symulacji komputerowych. Ponadto, w artykule zaprezentowano wyniki pomiarów laboratoryjnych, w trakcie których generowano impulsy wyładowań niezupełnych w modelu kadzi transformatora energetycznego. Zarówno wyniki symulacji komputerowych jak i pomiarów laboratoryjnych wykazały, że prototypowa antena fraktalna Hilberta, dzięki takim własnościom jak: wielorezonansowość, małe wymiary, niski koszt produkcji oraz wysoka czułość, stanowi ciekawą alternatywę dla innych czujników UHF instalowanych w oknie rewizyjnym transformatora energetycznego.

### LEHRICH K, WĄSIK M, KOSMOL J. Identyfikacja przyczyn pogorszenia stanu powierzchni obrabianej na tokarce kolowej. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 352–358, http://dx.doi.org/10.17531/ein.2018.3.2.

Problemy eksploatacyjne są często wykrywane dopiero po uruchomieniu maszyny i po pierwszych próbach obróbki. Obrabiarki ciężkie są specyficzną grupą maszyn do obróbki ze względu na charakter ich procesu produkcyjnego. W procesach produkcyjnych tego typu maszyn, ze względu na jednostkowy charakter produkcji i koszty, nie buduje się wersji prototypowych i nie wykonuje się na nich testów. Tym samym, przed wersją ostateczną, metody symulacji komputerowych są często jedynymi narzędziami walidacji projektu na etapie projektowania. Różnorodność zastosowań i indywidualność produkcji sa przyczyna braku opracowanych norm określających sztywność i precyzję obróbki wykonywanej przez ciężkie obrabiarki. Autorzy rozpatrują przypadek tokarki ciężkiej do zestawów kół kolejowych, w której podczas eksploatacji stwierdzono pewne problemy, które uniemożliwiają wytwarzanie przy zadanych parametrach w celu osiągnięcia pożądanego kształtu, wymiarów i jakości powierzchni. W artykule przedstawiono kompleksowe podejście do identyfikacji kształtu i częstotliwości drgań własnych konstrukcji nośnej obrabiarki oraz ich potencjalnych źródeł, na przykładzie poziomej tokarki do zestawów kolejowych. Autorzy w swoich badaniach zgodnie z uzyskanymi wynikami i ich doświadczeniem z zakresu projektowania ciężkich obrabiarek i badań podkreślają drgania samowzbudne, które są rzadko brane pod uwagę w tego typu maszynach, ale mają znaczący wpływ na zachowanie modalne maszyny.

## PROCHOWSKIL. Ocena procesu narastania przebiegu podczas eksploatacji samochodów ciężarowych w kilku kategoriach pojemności silnika. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 359–370, http://dx.doi.org/10.17531/ein.2018.3.3.

W czasie wieloletniej eksploatacji samochodów zmianie ulega intensywność ich użytkowania oraz zakres realizowanych zadań transportowych. Zmiany te są rezultatem analizy kosztów eksploatacji, niezawodności oraz osiąganych parametrów trakcyjnych. Zmiany w procesie eksploatacji, które zachodzą wraz z wiekiem samochodów, analizowano na podstawie przebiegu prawie 9000 samochodów ciężarowych. Analizowany jest dwudziestoletni okres eksploatacji pojazdów. Rezultaty tej analizy wykorzystano podczas estymacji modeli matematycznych, które opisują zasadnicze cechy procesu narastania wartości przebiegu, pojawiające się w ostatnich latach wraz z intensywnym wzrostem transportu drogowego w Polsce. Opracowano modele narastania przebiegu w siedmiu kategoriach pojemności silnika. Podano współczynniki równań tych modeli oraz dokonano wszechstronnej oceny dokładności obliczonych na ich podstawie wartości przebiegu. Obliczone względne miary rozrzutu wartości przebiegu z tych modeli nie przekraczają 12% od wartości średnich, wyznaczonych z danych eksperymentalnych. Zaproponowano procedurę postępowania, która prowadzi do wyznaczenia oceny procesu narastania przebiegu i jest oparta na dotychczasowych doświadczeniach w tym zakresie. Pokazano, że proces narastania przebiegu ma silny związek z pojemnością silnika. Proces narastania przebiegu jest ważnym źródłem informacji podczas planowania eksploatacji pojazdów, prognozowania kosztów, a także oceny emisji spalin i zużycia energii w całym cyklu eksploatacji samochodów w firmach transportowych.

#### WALISZYN A, ADAMKIEWICZ A. **Metoda tłumienia drgań tulei cylindrowych silników o zapłonie samoczynnym zapobiegająca konsekwencjom erozji**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 371–377, http://dx.doi.org/10.17531/ein.2018.3.4.

W artykule uzasadniono potrzebę określenia drgań własnych tulei cylindrowych silników okrętowych o zapłonie samoczynnym. Opisano badania własne w tym zakresie: teoretyczne dotyczące drgań własnych i eksperymentalne, dotyczące drgań wymuszonych.W badaniach teoretycznych do modelowania zastosowano liczby kryterialne podobieństwa z wykorzystaniem środowiska cyfrowego Elektroniks Workbench i Wis Sim. Umożliwiły one modelowanie wirtualne drgań tulei cylindrowych i określenie ich charakterystyk: of their characteristics: amplitudes, frequencies and accelerations. In the theoretical examination mechanical and electrical system analogues have been applied. A calculation method for the cylinder liner vibration damper, developed as a result of the study, has been discussed. Electrical oscillation damping filter design methods basing on the Bessel, Batterword and Chebyshev polynomials have been used. The course of the experimental examinations has been described and their results have been presented. Validation of the developed method has been executed applying measurement results concerning the parameters of Diesel engine cylinder liner vibration with various elastic elements. The results of the authors' own, theoretical and experimental, examinations have been confronted with those obtained by other scholars.

## BALAC M, GRBOVIC A. PETROVIC A, POPOVIC V. FEM analysis of pressure vessel with an investigation of crack growth on cylindrical surface. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 378–386, http://dx.doi.org/10.17531/ein.2018.3.5.

To ensure reliability of pressure vessels during service it is necessary to (1) know properties of materials used in their design and (2) evaluate vessels' behaviour under different working conditions with satisfying accuracy. Due to various technical and/or technological requirements, nozzles are usually welded on vessel's shell producing geometrical discontinuities that reduce the safety factor. To evaluate their influence, vessels with two different nozzles were experimentally studied and critical areas for crack initiation have been identified by 3D Digital Image Correlation (DIC) method. After that, the numerical analysis of equivalent 3D finite element model was performed and obtained results were compared with experimental values. In the most critical area, next to the one of the nozzles, crack was initiated and then growth of the damage was simulated using extended finite element method (XFEM). In this paper evaluation of stress intensity factors (SIFs) along crack path is presented, as well as the most probable direction of the crack propagation on the shell. Based on SIFs values, critical length of the crack and number of pressure cycles to the final failure were estimated.

#### NIKOŃCZUK P. Preliminary modeling of overspray particles sedimentation at heat recovery unit in spray booth. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 387–393, http://dx.doi.org/10.17531/ ein.2018.3.6.

Overspray sediments settling on the recuperator's fins cause operational problems. The cross sections of the recuperator's channels gradually decrease and finally it result in clogging of the recuperator. The layers of sediments cause air flow resistance and also heat transfer resistance. The paper presents preliminary results of sedimentation process modeling. The model of overspray creation takes into account a droplets size and particles concentration in air stream inside extraction ducting. Simulation results are compared with measurements conducted in three commercial spray booths.

#### CHENG Z, REMENYTE-PRESCOTT R. Two probabilistic life-cycle maintenance models for the deteriorating pavement. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 394–404, http://dx.doi. org/10.17531/ein.2018.3.7.

Pavement maintenance management poses a significant challenge for highway agencies in terms of pavement deterioration over time and limited financial resources to keep the road condition at an acceptable level. In this paper two probabilistic maintenance models are proposed and compared for pavement deterioration and maintenance processes to evaluate different maintenance strategies. Firstly, the states of pavement condition are defined using the features of different pavement maintenance works, instead of using the traditional method of cumulative service index rating. Secondly, a Markovian model is presented to describe the pavement deterioration and maintenance process with some constraints on the number of interventions, the effect of interventions and etc. But for the complex scenarios, such as non-Markovian deterioration, dependencies between the different types of interventions and the usage of emergency maintenance for roads when the required budget for maintenance is unavailable, a simulation-based Petri-net model is built up to investigate the whole life-cycle evolution. Two examples are used to illustrate and compare the proposed models to demonstrate the merits and disadvantages of each model and its applicable conditions.

# JIMENEZ CORTADI A, IRIGOIEN I, BOTO F, SIERRA B, SUAREZ A, GALAR D. A statistical data-based approach to instability detection and wear prediction in radial turning processes. Eksploatacja i Nieza-wodnosc – Maintenance and Reliability 2018; 20 (3): 405–412, http://dx.doi. org/10.17531/ein.2018.3.8.

Radial turning forces for tool-life improvements are studied, with the emphasis on predictive rather than preventive maintenance. A tool for wear prediction in various experimental settings of instability is proposed through the application of two statistical approaches to process data on tool-wear during turning processes: three sigma

amplitudy, częstości i przyśpieszenia. W badanach tych zastosowano analogi układów mechanicznych i elektrycznych. Opracowano metodę tłumienia drgań tulei cylindrowych z zastosowaniem filtrów tłumienia drgań elektrycznych w oparciu o wielomiany Bessela, Batterworda i Czebyszewa. Opisano przebieg badań eksperymentalnych i pokazano otrzymane wyniki. Walidację opracowanej metody przeprowadzono wykorzystując wyniki pomiarów parametrów drgań tulei cylindrowej silnika spalinowego z różnymi elementami sprężystymi. Skonfrontowano wyniki badań własnych z wynikami badań innych badaczy.

#### BALAC M, GRBOVIC A. PETROVIC A, POPOVIC V. Analiza MES zbiornika ciśnieniowego z badaniem rozwoju pęknięć na powłoce walcowej. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 378–386, http://dx.doi.org/10.17531/ein.2018.3.5.

Aby zapewnić niezawodność zbiorników ciśnieniowych podczas pracy, konieczna jest (1) znajomość właściwości materiałów zastosowanych do ich konstrukcji oraz (2) wystarczająco dokładna ocena zachowania zbiornika w różnych warunkach pracy. Ze względu na różne wymagania techniczne i/lub technologiczne, króćce zwykle spawa się do płaszcza zbiornika, w wyniku czego powstają geometryczne nieciągłości, które zmniejszają współczynnik bezpieczeństwa. Aby ocenić ich wpływ, przeprowadzono eksperymentalne badania zbiorników z dwoma różnymi króćcami i określono obszary krytyczne dla inicjacji pęknięć wykorzystując metodę trójwymiarowej cyfrowej korelacji obrazu (DIC). Następnie przeprowadzono analizę numeryczną równoważnego modelu elementów skończonych 3D, a uzyskane wyniki porównano z wartościami eksperymentalnymi. W najbardziej krytycznym obszarze, w pobliżu jednego z króćców, inicjowano pęknięcie, a następnie symulowano rozwój uszkodzenia przy użyciu rozszerzonej metody elementów skończonych (XFEM). W artykule przedstawiono ocenę współczynników intensyfikacji naprężeń (SIF) wzdłuż ścieżki pękania oraz najbardziej prawdopodobnego kierunku propagacji pęknięć na płaszczu zbiornika. Na podstawie wartości SIF, oszacowano krytyczną długość pęknięcia i liczbę cykli ciśnieniowych do ostatecznego uszkodzenia.

#### NIKOŃCZUK P. Wstępny model sedymentacji osadów lakierniczych w rekuperatorze kabiny lakierniczej. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 387–393, http://dx.doi.org/10.17531/ ein.2018.3.6.

Odkładające się na lamelach rekuperatora osady lakiernicze powodują problemy eksploatacyjne. Przekroje poprzeczne kanałów rekuperatora stopniowo zmniejszają się i ostatecznie prowadzi to do zatkania rekuperatora. Oprócz oporów przepływu powietrza osady stanowią również opór termiczny przy wymianie ciepła. W artykule przedstawiono wstępne wyniki modelowania procesu sedymentacji drobin lakieru. Zaprzentowano model powstawania mgły lakierniczej zawierającej krople lakieru o określonej średnicy oraz stopień koncentracji drobin lakieru w kanale wentylacyjnym za filtrem. Wyniki symulacji porównano z wynikami pomiarów w rzeczywistych kabinach lakierniczych.

## CHENG Z, REMENYTE-PRESCOTT R. Dwa probabilistyczne modele eksploatacji niszczejącej nawierzchni drogowej. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 394–404, http://dx.doi.org/10.17531/ein.2018.3.7.

Zarządzanie utrzymaniem nawierzchni stanowi poważne wyzwanie dla agencji eksploatacji autostrad, ponieważ stan nawierzchni wraz z upływem czasu ulega pogorszeniu, a środki finansowe potrzebne na utrzymanie jej w stanie używalności są ograniczone. W niniejszej pracy zaproponowano dwa probabilistyczne modele utrzymania nawierzchni drogowej. Modele porównywano w odniesieniu do procesów niszczenia nawierzchni oraz jej konserwacji, celem oceny różnych strategii eksploatacji. Na wstępie określono stan nawierzchni na podstawie charakterystyk wykonanych prac konserwacyjnych, zamiast korzystania z tradycyjnej metody oceny narastającego wskaźnika obsługi technicznej. Po drugie, przedstawiono model Markowa opisujący procesy niszczenia i konserwacji nawierzchni, z pewnymi ograniczeniami dotyczącymi liczby napraw, wyników napraw, itp. W przypadku złożonych scenariuszy obejmujących niszczenie jako proces niemarkowowski, opisanie zależności między różnymi typami napraw oraz korzystania z konserwacji awaryjnej dróg, w przypadkach gdy wymagany budżet na konserwację jest niedostępny, wymaga skonstruowania modelu sieci Petriego opartego na symulacji. Model ten pozwala na zbadanie ewolucji całego cyklu życia nawierzchni. W pracy przedstawiono dwa przykłady umożliwiające porównanie wad i zalet proponowanych modeli. Przykłady ilustrują także warunki zastosowania tych modeli.

#### JIMENEZ CORTADI A, IRIGOIEN I, BOTO F, SIERRA B, SUAREZ A, GALAR D. Metoda wykrywania niestabilności i przewidywania zużycia w procesach toczenia promieniowego w oparciu o dane statystyczne. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 405–412, http:// dx.doi.org/10.17531/ein.2018.3.8.

Badano siły występujące w procesie toczenia promieniowego. Celem badań było wydłużenie żywotności narzędzi tokarskich, przy czym główny nacisk kładziono na konserwację predykcyjną, a nie zapobiegawczą. Zaproponowano technikę prognozowania zużycia w różnych warunkach eksperymentalnych niestabilności, która polega na zastosowaniu metod edit rule analysis and Principal Component Analysis (PCA). A Linear Mixed Model (LMM) is applied for wear prediction. These statistical approaches to instability detection generate results of acceptable accuracy for delivering expert opinion. They may be used for on-line monitoring to improve the processing of different materials. The LMM predicted significant differences for tool wear when turning different alloys and with different lubrication systems. It also predicted the degree to which the turning process could be extended while conserving stability. Finally, it should be mentioned that tool force in contact with the material was not considered to be an important input variable for the model.

KORNATKA M. Analysis of the exploitation failure rate in Polish MV networks. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 413–419, http://dx.doi.org/10.17531/ein.2018.3.9.

The paper presents an analysis of exploitation failure rate in MV overhead and cable lines and in MV/LV transformers in the Polish power system. The reliability analysis is carried out by means of a non-parametric method using kernel estimators. The data are obtained from power networks of various operating conditions, and because of that the weight of data is taken into consideration. Additionally, the paper offers an innovative way of presenting the reliability data in a graphic form.

GÖKDERE G. **Time-dependent system reliability under stress-strength setup**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 420–424, http://dx.doi.org/10.17531/ein.2018.3.10.

Consider a system which has *n* independent components whose time dependent strengths  $Y_1(t), Y_2(t), \ldots, Y_n(t)$  are independent identically distributed random processes. Let random processes  $X_1(t), X_2(t), \ldots, X_m(t)$  denote the common multiple stresses experienced by the components at time *t*. The reliabilities of the components in the system can chance as a result of their deterioration or in consequence of variable stresses over time. Degradation in components reliabilities in the system can lead to the degradation of the entire system reliability. In this paper, we propose a new method for determining the time dependent component reliability of the system under stress-strength setup. The proposed method provides a simple way for evaluating the reliability of the system at a certain time period. Computational results are also presented for the reliability of coherent system and consecutive *k*-out-of-*n* system.

#### RYMARCZYK T, KŁOSOWSKI G. Application of neural reconstruction of tomographic images in the problem of reliability of flood protection facilities. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 425–434, http://dx.doi.org/10.17531/ein.2018.3.11.

The article presents an innovative concept of enhancing the flood embankments and landfills monitoring. The key advantage of such a solution is to obtain a more detailed distribution of components within a flood barrier. It leads to more early and sufficient threat detection, considering the exploitation of the building, thus - a vast enhancement of a embankment's performance. The method is based on implementing a neural system, composed of a number of parallelly-working neural networks. Each of them generate a singular point of final output view. By implementing such monitoring measures it is possible to successfully reconstruct two-and-three dimensional models of flood barriers and dams - including possible breaches and damages within its inner structure. An important advantage of such a solution is the possibility of replacing the systems that monitor hydrotechnical facilities pixel-by- pixel by neural imaging. The performed research leads to solving the problem of low resolution of such images. As this problem was of crucial value to tomographic imaging method, it was a main obstacle to the development of neural reconstruction method. Moreover, as the results may be obtained in real-time and at various levels, these new functionalities stand out in comparison to currently used methods for monitoring protective banks.

PRZYBYŁEK P, GIELNIAK J. Concentration analysis of gases formed in mineral oil, natural ester, and synthetic ester by discharges of high energy. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 435–442, http://dx.doi.org/10.17531/ein.2018.3.12.

The paper describes physical foundations of gases generation in different electroinsulating liquids. The authors reviewed literature concerning the analysis of gases generated in these liquids as a result of discharges of low energy. The main purpose of the research was to compare gases formed in mineral oil, natural ester, and synthetic ester resulting from discharges of high energy, which has not been studied so far. The statystycznych do przetwarzania danych dotyczących zużycia narzędzi podczas procesów toczenia. Wykorzystano dwie metody statystycznę: analizę z zastosowaniem reguły trzech sigm oraz analizę głównych składowych (PCA). Do prognozowania zużycia zastosowano liniowy model mieszany (LMM). Omawiane statystyczne podejścia do wykrywania niestabilności generują wyniki o dopuszczalnej dokładności, na podstawie których można formułować opinie eksperckie. Dane te można wykorzystywać do doskonalenia przetwarzania różnych materiałów poprzez monitorowanie w trybie on-line. W przedstawionych badaniach, LMM pozwolił przewidzieć znaczące różnice w zużyciu narzędzia podczas toczenia róźnych stopów przy zastosowaniu róźnych systemów smarowania. Umożliwił także prognozowanie stopnia, w jakim proces toczenia można przedłużać zachowując jego stabilność. Na koniec należy wspomnieć, że nie brano pod uwagę siły generowanej w kontakcie narzędzia z materiałem jako istotnej zmiennej wejściowej dla modelu.

#### KORNATKA M. Analiza eksploatacyjnej awaryjności krajowych sieci średniego napięcia. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 413–419, http://dx.doi.org/10.17531/ein.2018.3.9.

W artykule przedstawiono wyniki analizy danych eksploatacyjnych awaryjności linii napowietrznych i kablowych średniego napięcia jak również transformatorów SN/nN krajowego systemu elektroenergetycznego. Do analizy zagadnienia zastosowano nieparametryczną metodę analizy danych niezawodnościowych sieci elektroenergetycznych z wykorzystaniem estymatorów jądrowych. Poszczególne dane pochodzą z sieci elektroenergetycznych mających różny charakter pracy, dlatego uwzględniono w analizie wagę poszczególnych danych. W artykule zaproponowano także nowy sposób prezentacji graficznej analizowanych danych niezawodnościowych.

## GÖKDERE G. **Obliczanie zmiennej w czasie niezawodności systemu na podstawie modelu wytrzymałości na obciążenia**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 420–424, http://dx.doi.org/10.17531/ ein.2018.3.10.

Rozważmy system, który posiada n niezależnych elementów, z których każdy charakteryzuje się zmienną w czasie wytrzymałością  $Y_1(t), Y_2(t), \ldots, Y_n(t)$ , która stanowi niezależny proces losowy o identycznym do pozostałych rozkładzie. Niech procesy losowe  $X_1(t), X_2(t), \ldots, X_m(t)$  oznaczają wielorakie obciążenia powszechnie oddziałujące na elementy systemu w danym czasie t. Niezawodność elementów w systemie może ulegać zmianie w wyniku ich deterioracji lub w wyniku oddziaływania zmiennych w czasie obciążeń. Pogorszenie niezawodności komponentów systemu może prowadzić do obniżenia niezawodności całego systemu. W niniejszym artykule proponujemy nową metodę określania zmiennej w czasie niezawodności składowych systemu na podstawie modelu obciążeń i odpowiadających im wartości wytrzymałości. Zaproponowana metoda zapewnia prosty sposób oceny niezawodności systemu w pewnym okresie czasu. Przedstawion orównież wyniki obliczeniowe dotyczące niezawodności systemu koherentnego oraz systemu szeregowego typu k -z-n.

RYMARCZYK T, KŁOSOWSKI G. Zastosowanie neuronowej rekonstrukcji obrazów tomograficznych w problematyce niezawodności zabezpieczeń przeciwpowodziowych. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 425–434, http://dx.doi.org/10.17531/ein.2018.3.11.

W artykule zaprezentowano nowatorską koncepcję usprawnienia monitoringu wałów i zapór przeciwpowodziowych. Główną przewagą nowego rozwiązania nad znanymi metodami jest uzyskanie dokładniejszego rozkładu komponentów wnętrza zapory, co zasadniczo przyczynia się do wczesnego i niezawodnego wykrycia zagrożeń związanych z eksploatacją tego typu budowli. Dzięki temu, zastosowanie nowej metody spowoduje wzrost niezawodności zabezpieczeń przeciwpowodziowych. W opisywanej metodzie założono wytrenowanie systemu neuronowego złożonego z wielu działających równolegle sięci neuronowych, z których każda generuje pojedynczy punkt obrazu wyjściowego. Powyższy sposób, uwzględniający jednoczesne zastosowanie wielu sieci neuronowych, umożliwia skuteczną realizację trudnych zagadnień rekonstrukcji obrazów dwu i trój-wymiarowych, w tym obrazowanie uszkodzeń i przecieków wnętrza zapór przeciwpowodziowych. Ważną zaletą prezentowanej metody jest możliwość zastąpienia obrazowaniem neuronowym wielu innych, obecnie stosowanych systemów, które monitorują budowle hydrotechniczne w sposób punktowy. Przeprowadzone badania umożliwiają rozwiązanie problemu niskiej rozdzielczości obrazów tomograficznych, co stanowi główną barierę rozwoju tych metod w odniesieniu do dużych budowli ziemnych. Poprawa rozdzielczości rekonstruowanych obrazów, a także możliwość ich uzyskiwania w różnych przekrojach w czasie rzeczywistym, są nowymi funkcjonalnościami, które wyróżniają obrazowanie neuronowe na tle obecnie stosowanych metod monitoringu wałów i zapór przeciwpowodziowych.

## PRZYBYŁEK P, GIELNIAK J. Analiza stężeń gazów powstających na skutek oddziaływania luku elektrycznego na olej mineralny oraz estry naturalne i syntetyczny. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 435–442, http://dx.doi.org/10.17531/ein.2018.3.12.

W pracy opisano podstawy fizyczne związane z powstawaniem gazów w różnych cieczach elektroizolacyjnych. Dokonano przeglądu literatury dotyczącego analizy gazów generowanych w tych cieczach w wyniku wyładowań zupełnych. Głównym celem badań było porównanie gazów powstających w oleju mineralnym, estrze naturalnym oraz estrze syntetycznym w wyniku oddziaływania na te ciecze wyładowań zupełnych comparison was done both in terms of gases composition and their concentration. The purpose of the research was to give an answer to the question: which of the analysed liquids ensure higher operation safety if there is a discharge of high energy in the insulating system.

# FELDSHTEIN E, PATALAS-MALISZEWSKA J, KŁOS S, KAŁASZNIKOWA, ANDRZEJEWSKI K. The use of *Plackett-Burman* plans and the analysis of expert opinions, in order to assess the significance of controllable parameters of the plasma cutting process. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 443–449, http:// dx.doi.org/10.17531/ein.2018.3.13.

This article evaluates the significance of controllable parameters in the plasma cutting process, using the Plackett-Burman Method and the Analysis of Expert Opinions Method. The plasma cutting process was tested using a WPA-6000 Compakt plasma cutter, on non-alloy steel, of the S235JR EN 10025-2:2007 grade, with a carbon equivalent of 0.35%. The effect of the thickness of the sheet, the current flow rate, the cutting speed, the gas pressure during cutting, the height of the torch during cutting, the pierce delay time and the initial pierce height, were analysed. The research revealed the influence of the controllable parameters tested, in the plasma cutting process, on selected output parameters, surface cut drag lines, the width of the kerf at the inlet and outlet, and the value of the perpendicularity of the kerf on the surface of the base. The greatest influences were recorded for intensity of cutting current, cutting speed and gas pressure during cutting. The results obtained were confirmed by the results of the analysis of expert opinions.

#### STASZAK Ż, GRZEŚ Z, RYBACKI P. A method of comparative studies on checkup sets to evaluate the technical condition of tractors. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 450–454, http:// dx.doi.org/10.17531/ein.2018.3.14.

In this paper the authors propose an original method of the numerical evaluation of checkup sets for the technical condition of an agricultural tractor. Information entropy required in diagnostic tests for a specific checkup set was used as the evaluation criterion. A formal description is given for the technical condition diagnostics of a tractor in its operation period, which is characterised by a high rate of average damage. The structural model was constructed using information entropy. This model accumulates the number of checkups, probability of specific damage types and assigns them a common numerical measure. The conducted logic analysis of the proposed method and the results obtained in experiments on its practical applicability in service stations indicate that the method adequately describes this area of machine operation and thus may be a measure of information effectiveness for checkup sets determining the machine technical condition.

#### PŁACZEK M, PISZCZEK Ł. Testing of an industrial robot's accuracy and repeatability in off and online environment. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 455–464, http://dx.doi. org/10.17531/ein.2018.3.15.

The paper discusses issues concerning the accuracy and repeatability tests of the positioning of the Kuka KR 16-2 industrial robot. The results of laboratory tests of an industrial robot, as well as a comparison of robot motion paths in the Robcad environment with the real robot motion paths are presented. In order to register movement paths in the laboratory conditions, the laser tracker Faro Vantage was used. Frequent necessity to correct programs of industrial robots created in the offline environment, is a results, among others, from the insufficient experience of people who carry out programming, the environment in which robots work and the parameters of the robots themselves, and therefore their accuracy and repeatability. It is connected with the extension of the start-up time and high costs. The work describes the measurement method and attempts to determine the influence of the type of route and motion parameters on the accuracy and repeatability of robot. The accuracy of mapping of simulated robot motion in a virtual environment was also verified.

## JIA X, CUI L, XING L. New insights into reliability problems for supply chains management based on conventional reliability model. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 465–470, http:// dx.doi.org/10.17531/ein.2018.3.16.

The paper aims to find the relationship between conventional reliability and supply chain reliability, and introduce and adapt conventional reliability models to the field of supply chains, expanding the horizon of solving supply chain reliability problems. Based on a comprehensive literature review, the paper summarizes definitions of reliability in supply chain systems and presents reliability system structures and reliability indexes for supply chains. Relationship and differences between conventional reliability and supply chain reliability are shown. Illustrative examples such as the supply chain reliability problem in China are provided to show how to convert a supply chain reliability problem into a conventional reliability problem and then solve it using reliability techniques in conventional reliability. o bardzo dużej energii, co dotychczas nie było przedmiotem badań. Porównania dokonano zarówno pod kątem składu gazów jak i ich stężenia. Wyniki badań miały przede wszystkim dać odpowiedź na pytanie: która z analizowanych cieczy charakteryzuje się większym bezpieczeństwem eksploatacji w sytuacji wystąpienia w układzie izolacyjnym wysokoenergetycznego wyładowania zupełnego.

# FELDSHTEIN E, PATALAS-MALISZEWSKA J, KŁOS S, KAŁASZNIKOW A, ANDRZEJEWSKI K. **Wykorzystanie planów** *Placketta-Burmana* i analizy opinii ekspertów w celu oceny istotności parametrów sterowalnych procesu cięcia plazmowego. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 443–449, http://dx.doi.org/10.17531/ein.2018.3.13.

W artykule dokonano oceny istotności parametrów sterowalnych procesu cięcia plazmowego za pomocą metody Placketta-Burmana i analizy opinii ekspertów. Badania procesu cięcia plazmowego przeprowadzono przy użyciu przecinarki plazmowej WPA-6000 Compakt na stali niestopowej konstrukcyjnej gatunku S235JR EN 10025-2:2007 z ekwiwalentem węglowym wynoszącym 0.35 %. Analizowano wpływ grubości blachy, natężenia prądu, prędkości cięcia, ciśnienia gazów podczas cięcia, odstępu palnika od blachy podczas cięcia, czasu dziurkowania oraz wysokości startu. Badania ujawniły wpływ badanych parametrów sterowalnych procesu cięcia plazmowego na wybrane parametry wyjściowe, w szczególności na skok śladów cięcia, na szerokość szczeliny na wejściu i wyjściu oraz na wartość prostopadłości szczeliny do powierzchni bazowej. Największe wpływy zarejestrowano dla natężenia prądu, prędkości cięcia oraz ciśnienia gazu podczas cięcia. Otrzymane wyniki badań zostały potwierdzone wynikami analizy opinii ekspertów.

## STASZAK Ż, GRZEŚ Z, RYBACKI P. Metoda badań porównawczych zbiorów sprawdzeń do oceny stanu technicznego ciągników. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 450–454, http://dx.doi. org/10.17531/ein.2018.3.14.

W pracy zaproponowano oryginalną metodę liczbowej oceny zbiorów sprawdzeń stanu technicznego ciągnika rolniczego. Jako kryterium oceny wykorzystano entropię informacyjną, konieczną do uzyskania w badaniach diagnostycznych dla odpowiedniego zbioru sprawdzeń. Wykonano formalny opis procesu oceny stanu technicznego ciągnika w systemie eksploatacji, który charakteryzuje duży udział uszkodzeń awaryjnych. Do budowy modelu strukturalnego wykorzystano entropię informacyjną, Model ten kumuluje w sobie liczbę sprawdzeń, prawdopodobieństwo wystąpienia określonych uszkodzeń i nadaje im wspólną miarę liczbową. Przeprowadzona logiczna analiza proponowanej metody oraz wyniki uzyskane w badaniach z jej praktycznego zastosowania w zakładach serwisowych wskazują, że opisuje adekwatnie ten obszar eksploatacji maszyn i może być miarą efektywności informacyjnej zbiorów sprawdzeń stanu technicznego maszyn.

#### PŁACZEK M, PISZCZEK Ł. Badania dokładności i powtarzalności pozycjonowania robota przemysłowego w środowiskach off i online. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 455–464, http://dx.doi. org/10.17531/ein.2018.3.15.

W pracy omówiono zagadnienia dotyczące badań dokładności i powtarzalności pozycjonowania robota przemysłowego Kuka KR 16-2. Przedstawiono wyniki badań laboratoryjnych robota przemysłowego, a także dokonano porównania ścieżek ruchu robota symulowanego w środowisku Robcad ze ścieżkami ruchu robota rzeczywistego. W celu rejestracji ścieżek ruchu w warunkach laboratoryjnych zastosowano laserowy tracker Faro Vantage. Częsta konieczność poprawy programów robotów przemysłowych utworzonych w środowisku offline wiąże się z wydłużeniem czasu uruchomienia i dużymi kosztami. W artykule opisano metodę pomiarów oraz podjęto próbę określenia wpływu rodzaju ścieżki dojazdu do punktów pomiarowych i parametrów ruchu na dokładność i powtarzalność pozycjonowania robota. Zweryfikowano także dokładność odwzorowania ruchu robota symulowanego w środowisku wirtualnym.

#### JIA X, CUI L, XING L. Nowe spojrzenie na problemy związane z niezawodnością w zarządzaniu łańcuchami dostaw z punktu widzenia tradycyjnego modelu niezawodności. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 465–470, http://dx.doi.org/10.17531/ein.2018.3.16.

Celem artykułu jest znalezienie związku między niezawodnością w ujęciu tradycyjnym a niezawodnością łańcuchów dostaw, a także wprowadzenie i dostosowanie tradycyjnych modeli niezawodności do badań nad łańcuchami dostaw, co pozwoli na rozszerzenie możliwości rozwiązywania problemów dotyczących niezawodności tych ostatnich. W oparciu o obszerny przegląd literatury, w artykule przedstawiono pokrótce definicje niezawodności w systemach łańcucha dostaw oraz omówiono struktury systemów niezawodności i różnice między niezawodności dla łańcuchów dostaw. Pokazano zależności i różnice między niezawodności da vrzumieniu tradycyjnym a niezawodnością łańcucha dostaw. Przedstawiono przykład problemu niezawodności łańcucha dostaw zaczerpnięty z realiów chińskich, ilustrujący jak można przekształcić problem niezawodności łańcucha dostaw w tradycyjny problem niezawodności owy, a następnie rozwiązać go za pomocą technik niezawodności. LI J, YAN M, YU J. **Evaluation on gas supply reliability of urban gas pipeline network**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 471–477, http://dx.doi.org/10.17531/ein.2018.3.17.

As one of the lifeline projects, an urban gas network is a complex system, as it requires maintenance of the supply capacity when any single pipeline is isolated due to failure. For such a system, its reliability needs to be evaluated. Considering that existing structural reliability and hydraulic reliability analyses reflect different aspects of the working conditions of an urban gas network, system reliability theory is employed to explain that only the gas supply reliability can achieve a comprehensive evaluation of the work capacity of the entire urban gas network, as it takes into account the combined influence of the structural reliability and hydraulic reliability. To calculate the parameters in the gas supply reliability evaluation, such as pipeline failure rate, flow reduction in the gas network under different failure conditions, etc., some research achievements in the field of structural reliability and hydraulic reliability are fully utilized. Then, the detailed calculation procedures of these parameters are given to evaluate the gas supply reliability in terms of operational and practical considerations. Finally, using an example of a simple double-loop gas network, the detailed process of the gas supply reliability evaluation of an urban gas network is described, and the feasibility of this evaluation method is also illustrated.

#### KĘPCZAK N, ROSIK R, PAWŁOWSKI W, SIKORA M, WITKOWSKI B, BECHCIŃSKI G, STACHURSKI W. The dynamics of wear of cutting inserts during turning of non-homogeneous material on the example of polymer concrete. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 478–483, http://dx.doi.org/10.17531/ein.2018.3.18.

The article presents the results of studies on the dynamics of wear of five different cutting inserts (for machining difficult-to-cut materials, for finishing cast iron machining, for roughing cast iron machining, for steel machining and for stainless steel machining) during turning a non-homogeneous material such as polymer concrete. Polymer concrete is a difficult-to-cut, anisotropic, composite material. During the tests, a record of the components of the cutting force in real time was made. After each machining pass, the Ra and Rz surface roughness values were measured in the direction perpendicular to the machining marks and photos were taken under the microscope of the inserts corners, on the basis of which the width of major flank wear land and the width of minor flank wear land were measured. The view of each insert after the tests was also presented. Finally, the conclusions about the dynamics of wear of inserts taking part in the study as well as their applicability during polymer concrete turning were formulated.

### ANTOSZ K. Maintenance – identification and analysis of the competency gap. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 484–494, http://dx.doi.org/10.17531/ein.2018.3.19.

The efficiency of maintenance processes in an enterprise largely depends on ensuring adequate resources for its implementation. The main factor that affects the quality of these processes is competent employees. Their knowledge, skills and ability to respond to unexpected situations largely determine the efficiency of the functioning of the technical infrastructure in an enterprise. In the light of the prospects for the development of the Industry 4.0 concept, and, thus, for the development of highly automated systems, the demand for qualified maintenance employees will increase. Therefore, in order to ensure the right level of competency of maintenance workers, through the proper assessment and identification of their competency gap, is an important task of managers. In many enterprises this is not implemented. The aim of the presented work was to developed a comprehensive model of the competency assessment of maintenance workers. The implementation of the developed model enables the identification of the current level of employees' competencies and identification of the competency gap, as well as it allows to assess the effects of a failure to meet the required level of competency. Additionally, the results of the identification of the real activities taken by the surveyed enterprises concerning the competency assessment of maintenance services employees are presented in this article. The study was carried out in manufacturing enterprises in different industries on a specific area. The results were analysed and presented in a graphic form.

KARWAT B, MACHNIK R, NIEDŹWIEDZKI J, NOGAJ M. Selecting operating parameters of an electrostatic precipitator decreasing emission of solid fuels fly ashes. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 495–501, http://dx.doi.org/10.17531/ein.2018.3.20. The article presents the results of research aimed at developing the construction of an ESP (electrostatic precipitator), as well as the performance and selection of operating parameters of the ESP for household applications. The object of the experiment was the ESP prototype, designed and made by the authors, assigned to be placed in a gas pass of a detached house. A simulation of dustiness caused by burning solid fuels has been done. The experiment has been carried out for two different degrees of dust concentration at the ESP inlet, by controlling the given voltage. The results

LI J, YAN M, YU J. **Ocena niezawodności dostaw gazu w miejskiej sieci gazowej**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 471–477, http://dx.doi.org/10.17531/ein.2018.3.17.

Miejska sieć gazowa - jeden z kluczowych elementów infrastruktury miasta - stanowi złożony system, ponieważ wymaga utrzymania zdolności przesyłowej gdy przepływ gazu w jednym z rurociągów zostaje zamknięty w wyniku awarii. W przypadku tego rodzaju systemów, konieczna jest ocena niezawodności. Biorąc pod uwagę, iż dostępne w literaturze analizy niezawodności konstrukcyjnej i niezawodności hydraulicznej odzwierciedlają różne aspekty warunków pracy miejskiej sieci gazowej, nie dają one pełnego obrazu niezawodności systemu jako całości. W artykule wykorzystano teorię niezawodności systemów, która pokazuje, że jedynie ocena niezawodności dostaw gazu stanowić może kompleksową ocenę wydajności pracy całej miejskiej sieci gazowej, ponieważ uwzględnia ona zarówno wpływ niezawodności konstrukcji jak i niezawodności hydraulicznej sieci. W pracy wykorzystano dotychczasowe obserwacje badawcze dotyczące oceny niezawodności konstrukcyjnej i niezawodności hydraulicznej sieci gazowej do obliczenia parametrów oceny niezawodności dostaw gazu, takich jak intensywność uszkodzeń rurociągu, redukcja przepływu gazu w sieci gazowej w różnych warunkach uszkodzeń, itp. Następnie, podano szczegółowe procedury obliczania tych parametrów w celu oceny niezawodności przesyłowej sieci gazowej pod kątem eksploatacyjnym i praktycznym. Na koniec, na przykładzie prostej sieci gazowej składającej się z dwóch petli, opisano szczegółowy proces oceny niezawodności dostaw gazu w miejskiej sieci gazowej i zilustrowano możliwość wykorzystania proponowanej metody.

#### KĘPCZAK N, ROSIK R, PAWŁOWSKI W, SIKORA M, WITKOWSKI B, BECHCIŃSKI G, STACHURSKI W. **Dynamika zużycia płytek skrawających** podczas toczenia niejednorodnego materiału na przykładzie polimerobetonu. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 478–483, http://dx.doi.org/10.17531/ein.2018.3.18.

W niniejszym artykule zaprezentowano wyniki badań dynamiki zużycia pięciu różnych płytek skrawających (do obróbki materiałów trudnoobrabialnych, do wykończeniowej obróbki żeliwa, do zgrubnej obróbki żeliwa, do obróbki stali oraz do obróbki stali nierdzewnej) podczas toczenia niejednorodnego materiału, jakim jest polimerobeton. Polimerobeton jest trudnoobrabialnym, anizotropowym materiałem kompozytowym. Podczas wykonywania badań dokonywany był zapis składowych siły skrawania w czasie rzeczywistym. Po wykonaniu każdego przejścia obróbczego zostały zmierzone wartości parametrów chropowatości Ra oraz Rz obrobionej powierzchni w kierunku prostopadłym do śladów obróbki oraz zostały wykonane zdjęcia pod mikroskopem naroży płytek, na podstawie których zmierzono zużycie głównej powierzchni przyłożenia oraz pomocniczej powierzchni przyłożenia. Zaprezentowano również wygląd każdej z płytek po przeprowadzonych badaniach. Na koniec sformułowano wnioski na temat dynamiki zużycia płytek biorących udział w badaniu, a także stosowalności ich podczas toczenia polimerobetonu.

### ANTOSZ K. Utrzymanie ruchu – identyfikacja i analiza luki kompetencyjnej. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 484–494, http://dx.doi.org/10.17531/ein.2018.3.19.

Efektywność działań utrzymania ruchu w przedsiębiorstwie w dużej mierze zależy od zapewnienia odpowiednich zasobów do jego realizacji. Podstawowym czynnikiem, który ma wpływ na jakość realizacji tych działań są kompetentni pracownicy. Ich wiedza, umiejętności i zdolności reagowania na nieprzewidziane sytuacje, w dużej mierze decydują o sprawności funkcjonowania posiadanej infrastruktury technicznej w przedsiębiorstwie. W świetle perspektyw rozwoju koncepcji Przemysł 4.0, a tym samym rozwoju wysoce zautomatyzowanych systemów, wzrośnie zapotrzebowanie na wykwalifikowanych pracowników utrzymania ruchu. Dlatego ważnym zadaniem menedżerów przedsiębiorstw jest zapewnienie właściwego poziomu kompetencji pracowników utrzymania ruchu, poprzez ich odpowiednią ocenę i identyfikację luki kompetencyjnej, co w wielu przedsiębiorstwach nie jest realizowane. Celem przedstawionej pracy było opracowanie kompleksowego modelu oceny kompetencji pracowników utrzymania ruchu. Zastosowanie opracowanego modelu umożliwi identyfikację aktualnego poziomu kompetencji pracowników, identyfikację luki kompetencyjnej, jak również pozwoli ocenić skutki niezapewnienia wymaganego poziomu kompetencji. Dodatkowo w pracy przedstawiono wyniki badań, których celem było zidentyfikowanie rzeczywistych działań realizowanych w przedsiębiorstwach w zakresie oceny kompetencji pracowników służb utrzymania ruchu. Badania przeprowadzono w przedsiębiorstwach produkcyjnych, w różnych branżach przemysłu na określonym obszarze. Wyniki badań opracowano i przedstawiono w postaci graficznej.

KARWAT B, MACHNIK R, NIEDŹWIEDZKI J, NOGAJ M. **Dobór parametrów eksploatacyjnych elektrofiltru obniżającego niską emisję pyłów pochodzących ze spalania paliw stałych**. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (3): 495–501, http://dx.doi.org/10.17531/ein.2018.3.20. W artykule przedstawiono wyniki badań, mających na celu opracowanie konstrukcji, wykonanie oraz dobór parametrów eksploatacyjnych elektrofiltru do zastosowań w gospodarstwach domowych. Obiektem badań był opracowany i wykonany przez autorów prototyp elektrofiltru przeznaczony do montaż w kanale spalinowym budynku jednorodzinnego. Istotnym problemem jest dobór odpowiedniej elektrofy ulotowej. Zasymulowano zapylenie powstające na skutek spalania paliw stałych. Badania przeprowadzono dla dwóch różnych stężeń pyłów na wlocie do elektrofiltru, regulując podawane napięcie. Uzyskane proved that the proposed constructional solution of the ESP significantly limits low emission PM2.5 and PM10 dust emitted during the process of burning solid fuels: coal and/or biomass in boilers and fireplaces used in households or in small local boiler houses.

wyniki wykazały, że przyjęte rozwiązanie konstrukcyjne elektrofiltru umożliwia znaczne ograniczenie niskiej emisji pyłów PM2,5 i PM10 emitowanych w procesach spalania paliw stałych: węgla kamiennego i/lub biomasy w kotłach lub kominkach stosowanych w gospodarstwach domowych lub małych kotłowniach lokalnych.

### SCIENCE AND TECHNOLOGY

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#### HILBERT CURVE FRACTAL ANTENNA FOR DETECTION AND ON-LINE MONITORING OF PARTIAL DISCHARGES IN POWER TRANSFORMERS

#### ANTENA FRAKTALNA HILBERTA DO DETEKCJI I MONITORINGU WYŁADOWAŃ NIEZUPEŁNYCH W TRANSFORMATORACH ENERGETYCZNYCH

This article describes the design of UHF Hilbert curve fractal antenna (HCFA) specially adapted for the partial discharge monitoring system. The authors present the mathematical apparatus for calculating resonant frequencies of Hilbert fractal antenna and results of a computer simulation of the developed prototype. In the design process, the antenna's working environment (mineral oil) and the mechanical construction of the transformer inspection window were taken into consideration as well. The article also shows the results of laboratory tests carried out in the transformer tank model with different type of partial discharge sources. Both simulations and partial discharge measurements showed that the HCFA, due to such properties as: multi-resonance, small size, low fabrication cost and high sensitivity, is an interesting alternative to other UHF probes installed in transformer inspection window.

*Keywords:* fault diagnosis and maintenance of power transformers, partial discharge detection and monitoring, UHF method, Hilbert curve fractal antenna.

W artykule zaprezentowano projekt anteny fraktalnej Hilberta przeznaczonej do stosowania w systemach monitoringu wyładowań niezupelnych wykorzystujących metodę UHF. Autorzy szczegółowo opisali aparat matematyczny służący do estymacji częstotliwości rezonansowych anteny fraktalnej Hilberta oraz wyniki symulacji komputerowych. Ponadto, w artykule zaprezentowano wyniki pomiarów laboratoryjnych, w trakcie których generowano impulsy wyładowań niezupełnych w modelu kadzi transformatora energetycznego. Zarówno wyniki symulacji komputerowych jak i pomiarów laboratoryjnych, wykazały, że prototypowa antena fraktalna Hilberta, dzięki takim własnościom jak: wielorezonansowość, małe wymiary, niski koszt produkcji oraz wysoka czułość, stanowi ciekawą alternatywę dla innych czujników UHF instalowanych w oknie rewizyjnym transformatora energetycznego.

*Slowa kluczowe*: diagnostyka uszkodzeń i eksploatacja transformatorów energetycznych, detekcja i monitoring wyładowań niezupelnych, metoda UHF, antena fraktalna Hilberta.

#### 1. Introduction

Large power transformers are the most critical component in electric power systems, as they are essential in maintaining a reliable supply of electric energy. There are many factors which cause a transformer malfunction, but those, which can potentially lead to catastrophic failure are winding damages (due to short-circuit, lightning, and other over-voltages) and insulation system failure (moisture, thermal aging, partial discharges). The damage from a catastrophic transformer failure may run into tens of millions of dollars [16]. To avoid such a scenario, power utilities are moving towards continuous transformer condition monitoring, based on dissolved gas analysis and acoustic emission (AE) or electromagnetic (HF/VHF/UHF) partial discharge detection.

According to the newest research results and analyses presented by the experts of the CIGRE Working Group A2.37, in the technical brochure *642: Transformer Reliability Survey*, the main reason of breakdowns of high voltage power transformers is damage to the windings and the main insulation system [3]. Mechanical defects in the form of winding deformations (axial displacements and radial deformations) and deterioration of insulation properties associated with thermal aging processes [6], can lead to the initiation of the partial discharge (PD) phenomena occurrence.

In recent years, in the electric power industry and research centres, a trend consisting in developing and implementing advanced on-line PD monitoring systems is observed. These systems are able to detect and warn against defects occurring in a high-voltage insulating system. These monitoring systems most often work on the basis of one of the three relatively well-known and developed diagnostic methods, i.e.: (i) dissolved gas analysis in oil (DGA), (ii) detection of the acoustic emission signals (AE), and (iii) detection of electromagnetic waves in different frequency bands (HF/VHF/UHF) [8, 12, 17, 21, 23, 25, 28, 30].

Electromagnetic PD detection methods are already widely applied in diagnostics of gas insulated lines and substations (GIL/GIS), rotating machines, cables and medium voltage substations [1, 13]. At present, intensive research is being done on the development, implementation, and standardization of electromagnetic methods (particularly the UHF method) in the diagnostics of power transformers [9]. The research is mainly concentrated on development of new designs of sensitive UHF antennas. They are mechanically adapted for their installation in the inspection window (hole) of a transformer tank or the oil drain valve and on implementing on-line monitoring systems with included expert functions based on artificial intelligence algorithms (e.g. the function of automatic fault recognition or the function of generating warnings and alerts on the basis of trend analysis and accumulated knowledge base) [14–15, 20, 24].

#### 2. Design of UHF antenna for partial discharge detection: general requirements

Partial discharge monitoring systems, which functioning is based on recording electromagnetic pulses in the range of ultra-high frequencies (UHF) are gaining their growing popularity due to high resistance to external electromagnetic interference (EMI) and relatively high detection sensitivity of the discharges. Measurement probes (UHF antennas) are installed inside the steel transformer tank, shielding from external interference. For this purpose, inspection windows are used, which unfortunately means the necessity to pump out a large volume of insulating oil, or in available oil drain valves, which does not require switching off the unit. Examples of commercial designs of UHF antennas used for PD monitoring in power transformers are shown in Figure 1.

In order to design a UHF antenna, optimized for monitoring partial discharges generated in the paper/oil insulation system of the power transformer, one should take into consideration both numerous electric parameters which affect detection sensitivity of the PD phenomena, and mechanical ones, which will provide proper tightness and resistance to difficult environment conditions (high pressure and temperature inside the transformer tank, acidity of mineral oil, etc.). frequency of partial discharges. The laboratory and field investigations conducted so far, reveal that partial discharges generate UHF signals in a wide frequency band from about 200 MHz to 2 GHz [18]. Unfortunately, such a wide band covers different sources of radio signals (e.g. radio broadcasting stations or digital television transmitters). This involves the necessity to design more complicated antennas, which have a multi-band (multi-resonance) frequency response, which allows high sensitivity of PD detection and at the same time, resistance to narrow-band interference signals. The issue of proper matching the antenna's working band is more widely discussed in Section 3.

Another parameter of the antenna is input impedance. Due to connections made with coaxial cables, applied connectors, input impedance of the amplifiers, and the measurement equipment used for checking the parameters, the antenna's input impedance should be equal or close to 50  $\Omega$ . It is a standard generally accepted in radio communication. The level of impedance matching is described by means of the Voltage Standing Wave Ratio (VSWR) or Return Loss (RL).

It is assumed for the broadcast-receiving antennas in semi-professional system that the value of VSWR = 2 (RL = 9.5 dB), which means that 11.1% of the power will be reflected from the antenna input (the signal will decrease by 0.5 dB). In reality, for antennas in mobile phones, the commonly assumed threshold is VSWR = 2.5 or RL = 7.4 dB (reflection of 18.4% of the power from the antenna input or increase of signal attenuation by 0.9 dB). For receiving antennas which, for example, monitor the electromagnetic spectrum, the acceptable value is still VSWR = 3 or RL = 6 dB (reflection of 25% of power or signal attenuation equal to 1.25 dB). Signal attenuation of 3 dB is acceptable for discharge detection, especially when an amplifier which rises the power level of the received signals is applied. It should be noted that input impedance of the antenna is strongly affected by the working environment (space around the antenna), particularly objects made of conducting materials.

The antenna also has its own radiation pattern and a parameter linked with it, called antenna's power gain. For antennas placed inside the transformer tank, it is favourable to use antenna with an omnidirectional radiation pattern. Thus we will obtain an increase of the antenna's power gain and sensitivity increase of PD detection (the increase of the antenna's power gain means voltage signal increase on the antenna's output at the same electric field intensity of the received wave).

The value of the antenna's power gain is directly linked with the antenna factor, which can be useful for investigations of absolute values of electric field intensity in the transformer.



The antenna applied in a power transformer should also meet other requirements. One includes here resistance to high temperature in the range of 80-90°C, resistance to harmful influence of the oil (the condition for antennas immersed in the oil), or resistance to mechanical vibrations. The antenna placed in the dielectric window should be shielded from the external electromagnetic interferences, if possible. Shielding should reduce the level of interfering signals (radio, television, GSM etc.). The limits of mechanical dimensions are imposed by the dimensions of the inspection

Fig. 1. Schematic diagram and assembly example for UHF antenna installed in the inspection window (a), and in the oil drain valve (b)

window (the diameter of about 150 mm) and the oil drain valve (the diameter of about 20 mm).

#### 3. External radio frequency interferences

Wireless signal and data transmission very soon caused load of bandwidth in the UHF range. Developing telecommunications technologies, almost within all this range, make use of very strong transmitters and receivers. Their presence in close neighbourhood of the power substation can even disturb effective discharge detection because the transformer tank does not make a uniform Faraday cage. Unfortunately, the radio interferences can penetrate into transformer tank through bushings connected to HV transmission lines (Fig. 2). The main sources of radio interferences are:

- FM radio stations (87.5–108 MHz),
- aerial navigation systems (108–117.9 MHz),
- civilian and military aviation (117.9–143.9 MHz),
- transmitters of civil services (146–173.9 MHz),
- transmitters of DVB-T digital television (474–797 MHz),
- transmitters of GSM operators (890–960 MHz),
- LTE wireless internet (791–862 MHz).



Fig. 2. The radio frequency interferences entering the inside of the transformer tank

The presented above sources of VHF/UHF signals can act with different intensities in a given area. Their occurrence mainly depends on the location of the power substation, e.g. its distance from radio transmitters or the topography of the area where it is located. Analysing the issue of interfering signals, we may not ignore the interference coming from the electric power station itself, which source can be corona discharges from transmission lines or any connecting operations, such as connecting or disconnecting the line, transformer, generator, shunt reactor, capacitor battery or switching devices on the systems of busbar system in the substation.

Therefore, already at the early stage of the antenna designing process, the influence of external interferences has a fundamental significance and should be taken into account. A properly designed and produced antenna should have the properties of a multiband filter, i.e. provide high sensitivity in those frequency ranges, where the energy of partial discharges is transmitted (800–2000 MHz) and low sensitivity in the frequency ranges that are typical for interfering signals (< 800 MHz).

### 4. Designing and computer simulations of Hilbert curve fractal antenna for partial discharges detection

#### 4.1. Introduction

One of the most popular designs providing the required feature of multiband characteristic is fractal antenna. The application of the fractal theory allows considerable reduction of the size of the antenna without deteriorating its parameters, and this means that there is a relationship between the features of fractal geometry and electromagnetic properties of the antennas. The most important benefits referring to the application of fractal geometry in designing antennas are:

- more effective filling the space occupied by the antenna, which provides better energy transmission from the antenna feed line to the wave propagating in free space (this means better matching of input impedance),
- possibility to make (due to the property of self-similarity of fractals) multi-band antennas, i.e. antennas with a few resonance frequencies,
- lowering resonance frequencies in comparison to antennas of a traditional shape and similar dimensions,
- simple production process and easy for automation,
- possibility to obtain demanded properties without the necessity (as in the case of traditional antennas) to add concentrated reactive elements [29].

In the antenna technology we use dipoles, monopoles, loop or planar antennas of the geometry of the most popular fractals: Koch [2], Minkowski [5], Sierpinski [3], and also Hilbert fractal [26], which was applied by the authors. Hilbert fractal curve consists of the same, mutually perpendicular sections, which fill the surface of the square. An example of the first four iterations of Hilbert fractal is presented in Figure 3.



Fig. 3. The first four geometrical iterations of Hilbert's fractal

Filling the surface of a square antenna with the fractal curve is the reason of a relatively low resonance frequency. With an increasing number of iterations, the sum of fractal lines increases exponentially. This fact is useful at the moment of designing a small UHF antenna.

The concept to use the fractal curve for designing antennas is based on the effect observed in case of the meander line dipole antenna (Fig. 4a). In this approach, the inductance of the meander line, which consists of a line (creating a chain) of the letter-C shape is calculated [7, 10]. Next, the inductance of the straight line connecting all contours is added, in order to obtain the total inductance of the antenna. Finally, the obtained result is compared with the inductance of the half-wave dipole antenna.

The resonance feature of a dipole antenna occurs, when capacitive and inductive input reactances cancel each other. Assuming that input capacitive reactance of an antenna is constant, decreasing the apparent antenna length through bending of the antenna wire, the resonant condition is derived [27].

In the case of HCFA (Fig. 4b) of the external dimension l and subsequent iterations n (order of fractal), the length of each segment d is expressed by [27]:

a)



Fig. 4. Schematic diagram of: a) meander dipole antenna, b) Hilbert fractal antenna made of parallel sections A of the length of d and diameter b (bold line), segments connecting ends of parallel sections B (thin line), and segments connecting C (dashed line, length d)

$$d = \frac{l}{2^n - 1} \tag{1}$$

The geometry obtained after the fourth iteration (n=4) is shown in Figure 3. Moreover, in the HCFA geometry of order 4, there is  $m=4^{n-1}$  of the parallel compact sections, which consist of segments, each of the length of *d*. As it was shown in Figure 4a, for the segments which do not make parallel sections, their total length *s* is equal to:

$$s = \left(2^{2n-1} - 1\right)d$$
 (2)

The impedance of the parallel sections A which consists of wires of the diameter b and distance d is:

$$Z_0 = \frac{\eta}{\pi} \log \frac{2d}{b} \tag{3}$$

where  $\eta$  is intrinsic impedance of the free space. Equation (3) can be used for calculating input impedance at the line ends, which has purely inductive character:

$$L_{in} = \frac{Z_0}{\varpi} \tan \beta d \tag{4}$$

where  $\beta$  stands for reduction factor [10]:

$$\beta = \frac{l}{d\left(4^n - 1\right)} \tag{5}$$

The antenna has m sections, where self-induction of a single straight line of the length of s determined in Equation (2) is equal to:

$$L_s = \frac{\mu_0}{\pi} s \left( \log \frac{8s}{b} - 1 \right) \tag{6}$$

Substituting Equation (3) into Equation (4) and adding to (6), we can determine the antenna's total inductance  $L_T$ :

$$L_T = \frac{\mu_0}{\pi} s \left( \log \frac{8s}{b} - 1 \right) + m \frac{\eta}{\pi \omega} \log \frac{2d}{b} \tan \beta$$
(7)

In order to find HCFA resonance frequency, all its total inductance is compared with the inductance of the half-wave dipole antenna (of the approximate antenna length  $l=2/\lambda$ ) of the same resonance frequency. This leads to the condition determining the first HCFA resonance frequency, i.e.:



Fig. 5. Calculated values of the first few resonant frequencies for HCFA with different external dimension (l = 80, 100 and 120 mm), wire diameter b = 2 mm, and different fractal order: n = 3 (a), n = 4 (b), n = 5 (c)

$$m\frac{\eta}{\pi\omega}\log\frac{2d}{b}\tan\beta d + \frac{\mu_0}{\pi}s\left(\log\frac{8s}{b} - 1\right) = \frac{\mu_0}{\pi}\frac{\lambda}{4}\left(\log\frac{2\lambda}{b} - 1\right) (8)$$

It should be noted that dipole antennas resonate when the arm length is a multiple of the quarter wavelength. By this means, changing values linked with the wave length on the right side of equation (8), one can obtain all resonance frequencies of a multiband HCFA. Therefore, a few of the first resonance frequencies of HCFA can be determined on the basis of the following equation:

$$m\frac{\eta}{\pi\omega}\log\frac{2d}{b}\tan\beta d + \frac{\mu_0}{\pi}s\left(\log\frac{8s}{b} - 1\right) = \frac{\mu_0}{\pi}\frac{k\lambda}{4}\left(\log\frac{8}{b}\frac{k\lambda}{4} - 1\right)(9)$$

where k is an odd integer [24].

The way in which the antenna geometry (fractal order, external dimension) affects its resonant frequencies is shown in the Figure 5. The calculations were performed based on formula given in Equation (9).

Hilbert fractal antenna, due to its unique geometrical design, which consists of perpendicularly arranged segments, can be easily modelled in available software for numerical analysis and modelling of antenna design [4].

#### 4.2. Computer simulation results

The authors initially assumed that the prepared design should be of overall small dimensions and allow easy installation in the transformer inspection window with a built-in dielectric window (see Fig. 1a). On the basis of the catalogue data of the dielectric window designs available on the market, the authors decided to reduce the antenna dimensions down to a square of the side length equal to 110 mm (Fig. 6). For the needs of the simulation, it was assumed that the antenna will be made using the microstrip technology on the glass-reinforced epoxy laminate (FR-4), 1.5 mm thick. Additionally, the antenna model included a uniform copper reflector of the dimensions 110×110 mm and N-type connector.



Fig. 6. The schematic diagram and dimensions of investigated Hilbert curve fractal antenna of the 4th order

Farfield Directivity Abs (Phi=90)



Fig. 7. Simulated two-dimensional (a) and three-dimensional (b) radiation pattern for the proposed Hilbert curve fractal antenna of the 4th order at 1.5 GHz

In order to determine the voltage standing wave ratio (VSWR) and the radiation pattern, the CST Studio Suite® package was used. The VSWR parameter describes the impedance matching of the antenna to the transmission line. When the antenna is not matched to the receiver, power is reflected. This causes a "reflected voltage wave", which creates standing waves along the transmission line. The minimum VSWR is 1.0. In this case, no power is reflected from the antenna, which is ideal situation. As mentioned before in Section 2, the antenna has good sensitivity if the VSWR value in the working bandwidth is less than 3.0.

The obtained simulation results show that investigated HCF antenna has, at 1.5 GHz, broad radiation pattern with main lobe magnitude of 4.8 dBi and -3 dB angular bandwidth of 71° (Fig. 7), while the acceptable low values of VSWR parameter occur in the range of higher frequencies (over 800 MHz) and the investigated design of Hilbert fractal antenna has the ability to filtrate radio signals from most of the transmitting stations mentioned in Section 3. The lowest values of VSWR occur in the frequency band above 1500 MHz, which is free of the most of external radio interferences (Fig. 8).

#### 4.3. Result of laboratory measurements

Figure 9 presents a picture of the fractal antenna's prototype prepared by the authors. In order to verify the results obtained by means of computer simulations, the authors did a measurement of real values of factor VSWR using a Rhode&Schwarz ZVL Vector Network Analyzer.

The measurement results showed that the prototype Hilbert fractal antenna, in comparison to the results obtained by means of computer simulation, are characteristic of considerably better impedance matching to the transmission line in the frequency band from 800 to 2000 MHz. In this range, the VSWR values at resonant frequencies are in the range from 1.08 to 1.91 (Fig. 10). Some differences in VSWR values obtained in the simulations can result from assuming some simplifications that accelerate the calculations, such as: decreasing dimensions of the transformer tank, omission of the active part (or



Fig. 8. Computer simulated VSWR for the proposed Hilbert curve fractal antenna of the 4th order

the insulating system with the discharge source) and the mechanical elements of the tank, dielectric window and the antenna housing.

In the next stage of the research, a laboratory experiment was performed to evaluate the effectiveness of partial discharge detection by a prototype antenna. For this purpose a model of oil-filled transformer tank was used  $(1200 \times 800 \times 900 \text{ mm})$ , where a prototype Hilbert curve fractal antenna, and a standard microstrip disk antenna with a diameter of 100 mm, were installed. The disk antenna was used as a refer-



Fig. 9. Prototype Hilbert curve fractal antenna (a) and a photograph presenting the way of its installation in the inspection window of a laboratory model of a power transformer tank (b)



Fig. 10. Measured VSWR values of the prototype Hilbert curve fractal antenna







Fig. 12. Applied electrode systems for generation of: (a) surface discharges on pressboard sample in oil with large normal component of field strength vector – defect #1, (b) surface discharges on pressboard sample in oil where the normal component of field strength vector is insignificant – defect #2; (c) partial discharges in oil wedge/gap (so called "triple junction") – defect #3



Fig. 13. Schematic diagram of the measurement set-up: U-high-voltage supply; Z-short-circuit current limiting resistor; OSC-oscilloscope; TT-transformer tank model filled with mineral oil; RA-reference disk antenna; PA-prototype Hilbert curve fractal antenna; ES-electrode system for partial discharges generation;  $C_K$  - coupling capacitor; CD - coupling device (measuring impedance); CC - connecting cable; M-conventional PD measuring instrument (in accordance with standard IEC 60270)

ence, because it is the most commonly used for power transformer and GIS/GIL diagnostics [11, 19]. The measured VSWR plot is shown in Figure 11.

Using the electrode systems shown in Figure 12, three main types of PD pulses occurring in oil-paper insulation were generated: (a) surface/creeping discharges on pressboard sample in oil with large normal component of field strength vector (*defect #1*), (b) surface discharges on pressboard sample in oil, where the normal component of field strength vector is insignificant (*defect #2*); (c) partial discharge in oil wedge/gap (so called "triple junction") – *defect #3*.

The distance between the antennas and the source of impulses was about 45 cm. Partial discharge pulses were detected simultaneously with both antennas and recorded using Textronix MDO3100 oscilloscope (sampling rate 5 GS/s). In addition, a conventional electrical method (IEC 60270) was used to make sure that the recorded pulses were related to partial discharges and not to external radio disturbances. All elements of the measuring set-up were placed in a shielded high-voltage laboratory. The schematic diagram of the measurement set-up is shown in Figure 13.

The results of the measurements showed that for all three insulation defects, the prototype HCFA, compared to the reference disk antenna, has a higher sensitivity of partial discharge detection at UHF. In the case of the defect #1, the average peakto-peak amplitude for prototype Hilbert fractal antenna was 43% higher, while for *defect #2* and *defect#3* it was 18% and 16% higher, respectively. The measurement data obtained using the conventional electrical method and both UHF antennas are presented in Table 1, while the comparative analysis of registered PD pulses is shown in Figure 14.

#### 5. Summary

Both simulation and measurement results confirmed that the designed Hilbert curve fractal antenna can be effectively used for partial discharges detection and easily adapted to installation in the inspection window of power transformer tank or GIS/GIL.

The performance of prepared HCFA compared to the widely used disk antenna

is, from 16% to 43% higher, depending on the type of insulation defect. Although the gain is slightly lower than expected, the proposed antenna also has other important advantages, such as: (i) wideband and multi-resonant, (ii) low fabrication cost (can be printed directly on the PCB), (iii) small dimensions (miniaturization), (iv) consistent performance over huge frequency range (frequency independent), (v) added inductance and capacitance without components, (vi) better matching of input impedance.

The relatively small gain is not a serious disadvantage, because in practice, it can be easily increased by using a RF amplifier.

Due to the fact, that the HCF antenna does not have fully omnidirectional radiation pattern, effective detection of partial discharge pulses using single HCF antenna – especially in a power transformer with a complicated internal structure – may be difficult to perform. This problem can be solved by installing several antennas, both on the side walls and on the top cover of transformer tank.





#### Table 1. Partial discharge measurement data

Partial discharge type	Surface dis- charges Pressboard barrier within needle-plane electrode sys- tem (defect #1)	Surface dis- charges Needle placed nearly horizon- tal to the press- board barrier (defect #2)	Partial dis- charges in oil wedge 'Triple junction' electrodes (defect #3)
Partial discharge inception voltage 18.5 kV		23.0 kV	15.5 kV
Average appar- ent charge	2.87 nC	418 pC	3.48 nC
Pulse length	~500 ns	~400 ns	~600 ns
Average peak-to- peak amplitude for reference disk antenna	239 mV	171 mV	280 mV
Average peak-to- peak amplitude for prototype Hilbert fractal antenna	342 mV	203 mV	326 mV

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Fig. 14. Comparison of UHF PD pulses recorded using the reference disk antenna and the prototype Hilbert fractal antenna from: insulation defect #1 (a), insulation defect #2 (b) and insulation defect #3 (c)

#### References

c)

- 1. Álvarez F, Garnacho F, Ortego J, Sánchez-Urán M Á. Application of HFCT and UHF Sensors in On-Line Partial Discharge Measurements for Insulation Diagnosis of High Voltage Equipment. Sensors 2015; 15 (4): 7360-7387, https://doi.org/10.3390/s150407360.
- Baliarda C P, Romeu J, Cardama A. The Koch monopole: a small fractal antenna. IEEE Transactions on Antennas and Propagation 2000; 44 (48): 1773-1781., https://doi.org/10.1109/8.900236.
- 3. CIGRE Technical Brochure 642, Transformer Reliability Survey, CIGRE Working Group A2.37, December 2015.
- 4. Darmawan M A, Khayam U. Design, simulation, and fabrication of second, third, and forth order Hilbert antennas as ultra high frequency partial discharge sensor. Proceedings of the Joint International Conference on Electric Vehicular Technology and Industrial, Mechanical, Electrical and Chemical Engineering (ICEVT & IMECE), Surakarta 2015: 319-322, https://doi.org/10.1109/ICEVTIMECE.2015.7496707.

- Dhar S, Ghatak R, Gupta B, Poddar D R. A Wideband Minkowski Fractal Dielectric Resonator Antenna. IEEE Transactions on Antennas and Propagation 2013; 61 (6): 2895-2903, https://doi.org/10.1109/TAP.2013.2251596.
- Dombek G, Nadolny Z. Liquid kind, temperature, moisture, and ageing as an operating parameters conditioning reliability of transformer cooling system. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2016; 18 (3): 413-417, https://doi.org/10.17531/ein.2016.3.13.
- Endo T, Sunahara Y, Satoh S, Katagi T. Resonant frequency and radiation efficiency of meander line antennas. Electronics & Commun. in Japan 2000; 83 (2): 52-58, https://doi.org/10.1002/(SICI)1520-6432(200001)83:1<52::AID-ECJB7>3.0.CO; 2-7.
- Fan J, Wang F, Sun Q, Bin F, Ye H, Liu Y. An Online Monitoring System for Oil Immersed Power Transformer Based on SnO2 GC Detector With a New Quantification Approach. IEEE Sensors Journal 2017; 17 (20): 6662-6671, https://doi.org/10.1109/JSEN.2017.2734072.
- Gulski E, Koltunowicz W, Ariaans T, Behrmann G, Jongen R, Garnacho F, Kornhuber S, Ohtsuka S, Petzold F, Sanchez-Uran M, Siodla K, Tenbohlen S. Cigre Technical Brochure 662. Guidelines for partial discharge detection using conventional (IEC 60270) and unconventional methods, Paris 2016.
- 10. Mohassel J-A R. Meander Antennas (Doctoral dissertation), The University of Michigan 1982.
- 11. Judd M D, Farish O, Coventry P F. UHF couplers for GIS sensitivity and specification. 10th Int. Symp. on High Voltage Engineering (ISH), Montreal 1997.
- 12. Judd M D, Yang L, Hunter I B. Partial Discharge Monitoring for Power Transformers Using UHF Sensors. Part 1: Sensors and Signal Interpretation, IEEE Electrical Insulation Magazine 2015; 21 (2): 5-14, https://doi.org/10.1109/MEI.2005.1412214.
- Koltunowicz W, Badicu L V, Broniecki U, Belkov A. Increased operation reliability of HV apparatus through PD monitoring, IEEE Transactions on Dielectrics and Electrical Insulation 2016; 23 (3): 1347-1354, https://doi.org/10.1109/TDEI.2015.005579.
- Li J, Li X, Du L, Cao M, Qian G. An Intelligent Sensor for the Ultra-High-Frequency Partial Discharge Online Monitoring of Power Transformers. Energies 2016; 9 (5): 383-398, https://doi.org/10.3390/en9050383.
- 15. Liu J, Zhang G, Dong J, Wang J. Study on Miniaturized UHF Antennas for Partial Discharge Detection in High-Voltage Electrical Equipment. Sensors 2015; 15 (11): 29434-29451, https://doi.org/10.3390/s151129434.
- 16. Paska J. Chosen aspects of electric power system reliability optimization. Eksploatacja i Niezawodnosc Maintenance and Reliability 2013; 15 (2): 202-208.
- 17. Przybyłek P, Siodła K. Application of capacitive sensor for measuring water content in electro-insulating liquids. Eksploatacja i Niezawodnosc Maintenance and Reliability 2016; 18 (2): 181-185, https://doi.org/10.17531/ein.2016.2.4.
- Raja K, Devaus F, Lelaidier S. Recognition of Discharge Sources Using UHF PD Signatures. IEEE Electrical Insulation Magazine 2002; 18 (5): 8-14, https://doi.org/10.1109/MEI.2002.1044316.
- Robles G, Albarracín R, Vázquez J L. Antennas in Partial Discharge Sensing System. Springer Science, Business Media Singapore 2015, https://doi.org/10.1007/978-981-4560-75-7\_95-1.
- Siegel M, Beltle M, Tenbohlen S, Coenen S. Application of UHF sensors for PD measurement at power transformers. IEEE Transactions on Dielectrics and Electrical Insulation 2017; 24 (1): 331-339, https://doi.org/10.1109/TDEI.2016.005913.
- Sikorski W, Walczak K, Przybylek P. Moisture Migration in an Oil-Paper Insulation System in Relation to Online Partial Discharge Monitoring of Power Transformers. Energies 2016; 9 (12): 1082-1098, https://doi.org/10.3390/en9121082.
- 22. Singhal S, Singh A K. CPW-fed hexagonal Sierpinski super wideband fractal antenna. IET Microwaves, Antennas & Propagation 2016; 10 (15): 1701-1707, https://doi.org/10.1049/iet-map.2016.0154.
- 23. Sun C, Ohodnicki P R, Stewart E M. Chemical Sensing Strategies for Real-Time Monitoring of Transformer Oil: A Review. IEEE Sensors Journal 2017; 17 (18): 5786-5806, https://doi.org/10.1109/JSEN.2017.2735193.
- 24. Szymczak C, Sikorski W. Projektowanie i optymalizacja anten UHF do monitoringu wyładowań niezupełnych w transformatorze energetycznym. Przegląd Elektrotechniczny 2016; 10: 75-80, https://doi.org/10.15199/48.2016.10.18.
- 25. Tenbohlen S, Beltle M, Siegel M. PD monitoring of power transformers by UHF sensors. 2017 International Symposium on Electrical Insulating Materials (ISEIM), Toyohashi, Japan 2017: 303-306, https://doi.org/10.23919/ISEIM.2017.8088747.
- 26. Vinoy K J, Jose K A, Varadan V K, Varadan V V. Hilbert curve fractal antennas with reconfigurable characteristics. 2001 IEEE MTT-S International Microwave Sympsoium Digest (Cat. No.01CH37157), Phoenix, AZ, USA 2001; 1: 381-384.
- 27. Vinoy K J, Jose K A, Varadan V K. Resonant Frequency of Hilbert Curve Fractal Antennas IEEE Antennas and Propagation Society International Symposium, Boston 2001, https://doi.org/10.1109/APS.2001.960180.
- 28. Walczak K, Sikorski W, Gil W. Wielomodułowy system monitoringu wyładowań niezupełnych oparty na metodach EA, HF i UHF. Przegląd Elektrotechniczny 2016; 10: 5-9, https://doi.org/10.15199/48.2016.10.02.
- 29. Yang X, Chiochetti J, Papadopoulos D, Susman L. Fractal Antenna Elements and Arrays. Applied Microwave & Wireless 1999: 34-46.
- Ziomek W, Kuffel E, Sikorski W, Staniek P, Siodła K. Location and recognition of partial discharge sources in a power transformer using advanced acoustic emission method. Przegląd Elektrotechniczny 2008; 84: 20-23.

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#### IDENTIFYING THE CAUSES OF DETERIORATION IN THE SURFACE FINISH OF A WORKPIECE MACHINED ON A RAIL WHEEL LATHE

#### IDENTYFIKACJA PRZYCZYN POGORSZENIA STANU POWIERZCHNI OBRABIANEJ NA TOKARCE KOŁOWEJ\*

Operational problems often remain undetected until a machine is commissioned and first machining is attempted. Heavy-duty machines are a specific group of machine tools due to the character of their manufacturing process. As they are often manufactured as single units, which involves high production costs, there are no prototype versions built and no tests are performed on them. Therefore, before the machine is complete, computer simulation methods are often the only validation tools of a machine project at the stage of designing. The variety of applications and the individuality of production are the reasons for the lack of standards defining the rigidity and precision of the cutting process performed by heavy machine tools. In this case analysis, the authors are considering a heavy duty rail wheel lathe, in which some issues were found during its exploitation which make it impossible to achieve the required shape, dimensions and surface finish, while working at set parameters. This article presents a comprehensive approach to the identification of the form and frequency of a machine tool supporting structure's self-vibrations and their potential sources in the case study of a horizontal lathe for railway wheelsets. The authors, drawing on the results of their long-standing research and their experience in the field of heavy machine tool design and testing, indicate self-excited vibrations as a key factor machine's operational behaviour, which is rarely considered in this type of machines.

Keywords: self-excited vibrations, modal analysis, finite element method, machine tool CNC.

Problemy eksploatacyjne są często wykrywane dopiero po uruchomieniu maszyny i po pierwszych próbach obróbki. Obrabiarki ciężkie są specyficzną grupą maszyn do obróbki ze względu na charakter ich procesu produkcyjnego. W procesach produkcyjnych tego typu maszyn, ze względu na jednostkowy charakter produkcji i koszty, nie buduje się wersji prototypowych i nie wykonuje się na nich testów. Tym samym, przed wersją ostateczną, metody symulacji komputerowych są często jedynymi narzędziami walidacji projektu na etapie projektowania. Różnorodność zastosowań i indywidualność produkcji są przyczyną braku opracowanych norm określających sztywność i precyzję obróbki wykonywanej przez ciężkie obrabiarki. Autorzy rozpatrują przypadek tokarki ciężkiej do zestawów kół kolejowych, w której podczas eksploatacji stwierdzono pewne problemy, które uniemożliwiają wytwarzanie przy zadanych parametrach w celu osiągnięcia pożądanego kształtu, wymiarów i jakości powierzchni. W artykule przedstawiono kompleksowe podejście do identyfikacji kształtu i częstotliwości drgań własnych konstrukcji nośnej obrabiarki oraz ich potencjalnych źródeł, na przykładzie poziomej tokarki do zestawów kolejowych. Autorzy w swoich badaniach zgodnie z uzyskanymi wynikami i ich doświadczeniem z zakresu projektowania ciężkich obrabiarek i badań podkreślają drgania samowzbudne, które są rzadko brane pod uwagę w tego typu maszynach, ale mają znaczący wpływ na zachowanie modalne maszyny.

Słowa kluczowe: drgania samowzbudne, analiza modalna, metoda elementów skończonych, obrabiarka CNC.

#### 1. Introduction

Due to the general tendency to increase machining efficiency and the evolution of machine tools toward the so called 'High Speed Cutting' direction, manufacturers of machine tools face new challenges. These are associated with the need for designing machine tools, where the engineering cannot be based on past experience and the tried and tested design solutions are no longer valid. Heavy-duty machine tools are a specific group of machine tools due to the nature of their production process [22, 23]. Bearing in mind a limited demand, the design and construction process as well as the manufacturing process are either small-scale or unit-intensive. As these machines are often manufactured as single units, which naturally results in high manufacturing costs, there are no prototype versions built and no tests are performed on them prior to the commissioning. Therefore, computer simulation methods are often the only validation tools available at the design stage, until the machine is complete. The variety of applications and the individuality of production are the reasons for the lack of standards, which would define the rigidity of the machine and the precision of the machining performed by heavy machine tools. The lack of prototype testing results in the fact that no corrections are made to wrongly designed solutions. Tight deadlines for new orders forces engineers to rely on tried and tested solutions, which are not always the optimal ones. Operational problems often remain undetected until a machine is commissioned and the first machining is attempted. The author's experience shows that these problems are often connected with forced and self-excited vibrations, which limit the machine's capabilities to meet the required cutting parameters. This situation also occurred in the case of the lathe discussed in this study. The dynamic properties of machine tools have a significant influence on the cut-

<sup>(\*)</sup> Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

ting process and are considered among the most significant for the evaluation of a machine tool's structure. They are often described by frequency characteristics which allow for evaluating the stability of the machine-process system. The machine's dynamic properties may influence the dimensional accuracy and the surface roughness of a workpiece [24]. The analysis of the dynamic properties of a cutting machine's support structures should be one of the basic steps of a machine tool construction process. This article presents a comprehensive approach to the identification of the form and frequency of machine tool supporting structure self-vibrations and their potential sources, using the example of a horizontal lathe for railway wheelsets.

The paper presents an innovative approach, unprecedented in the literature, to identify the causes of deterioration in surface finish of a workpiece machined on a rail wheel lathe. The approach is based on the use of numerical methods to determine the vibration frequencies of a workpiece being machined and of the machine components which are directly responsible for the accuracy of the cutting process.

#### 2. Materials and methods

#### 2.1. Characteristics of the research object

The smooth work of a rail with a wheelset requires a fixed profile and consistent quality of the wheelset contact surface. Specialised wheel and track lathes are used for this purpose. The application of a rail wheel lathe for the regeneration of the wheelset contact surface needs dismounting the wheelset. These machines require high precision and efficiency of the process due to the constantly increasing demands for precision of the running components. In the process of facing a wheelset, vibrations may occur as a result of e.g. uneven wear of the contact surfaces [6, 10, 16, 19, 22, 28, 29]. The rotation of an unbalanced wheelset may be a source of vibrations and instability of the cutting process. Furthermore, it may generate great cutting forces during the machining which are transferred to machine components. Consequently, a wheel lathe should have a rigid and vibration-resistant structure [5, 7, 15, 18, 21, 25].

The analysed machine belongs to the group of blind wheel lathes,

i.e. both the entry and the departure of a wheelset is from the front of the machine. During the machining the wheelset is fixed at both ends by means of claws ejected from the tailstocks. In addition, the wheelset rests on two rollers on either side and is frictionally driven by a third roller pressed against it from the top. This solution is currently becoming more and more popular. The use of a driving roller prevents the formation of a notch, which commonly occurs with solutions using driving centres. Such notch may be particularly dangerous in case of high-speed railways. This method of fixing increases the accuracy of rotation and reduces the radial runout. Also, the forces acting on the locating centres are reduced.

In order to effectively identify the causes of excessive vibrations in the lathe, an analytical and numerical analysis of vibrations in the "lathe – cutting process" system were applied. A hypothesis was formulated that a loss of stability of the "lathe – cutting process" system, i.e. the occurrence of self-excited vibrations was the cause of excessive vibrations. The analytical solution, that is increasing the limit of stability, requires determining the frequency of the self-excited vibrations in the first place, e.g. by solving the identity  $Im[K(j\omega)]=0$ , where: w – pulsation of self-excited vibrations,  $K[(j\omega)]$  transmission of the open system, and then by determining the stability reserve. The stability reserve may be changed, e.g. by decreasing the dynamic susceptibility of the mechanical system or by changing the reinforcement coefficient in the cutting process. This classical method is tedious and difficult in the analytical procedure. Thanks to the numerical method (FEM) it was possible to identify the probable frequency of self-excited vibrations and test changes in the dynamic susceptibility of the mechanical system resulting from structural changes proposed.

#### 2.2. Lathe model

Machining of a wheelset while maintaining the required cutting parameters showed the occurrence of vibrations in the LCWC system: (lathe, chuck, workpiece and cutting tool). In consequence, it was impossible to obtain the required machining accuracy and the resulting surface finish showed high waviness and roughness (Fig. 1).

Any attempts to identify the causes of this situation did not produce desirable results. Also, experimental studies according to [12], to determine the vibration frequencies occurring during the machining have been carried out (Fig. 2, Fig. 3).

An analysis of the kinematic chain of the propulsion system excluded the possibility of vibrations being induced in the propulsions. In order to determine the causes of vibrations and methods to counteract them, the finite element method was applied. A number of numerical analyses according to current trends in numerical simulations [2, 3, 4, 13, 14] were carried out on the lathe model for the evaluation of its static rigidity, the form and frequency of self-excited vibrations and the response of the system to harmonic extortion.

#### 2.3. FEM model

In order to determine the dynamic properties of the lathe model ANSYS software has been used. For simulations the modal analysis module has been applied. With this module the first modal shapes and the corresponding frequencies have been designated. Discrete models of the wheel lathe have been developed basing on a CAD 3D model. The support has been designed independent as a FEM model. All of



Fig. 1. Comparison of surface finish quality for different machining parameters A) A = 5mm, S= 99m/min, f = 1,5 mm/rot, d = 856mm B) A = 4mm, S= 90m/min, f = 1,5 mm/rot (21%) d = 856mm.



Fig. 2. Frequency spectrum of signals recorded on the milled diameter under load



Fig. 3. Frequency spectrum of signals recorded at the edge under load



Fig. 4. FEM model of the analysed lathe



Table 1. Material properites for FEM analysis

Property	Structural steel
Young's modulus [MPa]	2*10 <sup>5</sup>
Poisson's ratio	0.3
Density [kg/m <sup>3</sup> ]	7850

the models have been designed as solids. Discretisation of models has been performed basing on finite 3D eight-node elements of HEXA type and four-node of TETRA type. The total number of finite elements of the entire lathe model with a wheel set equals to 949791 with 4092309 nodes. Views of the lathe model after discretization are shown in the figure (Fig. 4). The method of adopting the boundary conditions for the model of the entire lathe resulted from its foundation. Therefore, all degrees of freedom have been taken at the foundation of the bed. Due to the fact that the lathe bodies have been made as steel welded, the same material properties (appropriate for steel) for all elements of the models were adopted (Tab. 1).

#### 3. Results and discussion

First of all, a modal analysis of the wheelset itself was performed by determining the frequencies and forms of self-excited vibrations

> for the support in the chuck (Fig. 5). The first of the bent forms is characterised by a frequency similar to the one obtained in experimental studies. The support in the chuck and accounting for the construction of the tailstocks should cause a decrease in the frequency and a better match with the results obtained during the experiment.

> Subsequently, a modal analysis of the machine with a mounted wheelset was performed. As a result of the analyses (Fig.6), the same frequency of vibrations of the supports, the tailstocks and the wheelset were found for the first two forms of self-excited vibrations. The frequencies found are lower than those determined for the wheelset itself, which is

due to the susceptibility of the wheelset supporting and locating system.

As a result of the analyses, it was also found that there was no effect of the change of the sliders' position on self-excited frequencies. It can be observed that all of the eight resonance frequencies identified coincide with the results of experiments, and certain modal shapes may have a negative influence on machining accuracy.

The results of this analysis (Fig. 7) show inadequate rigidity of the structure. Despite the relatively high static rigidity of the supports, as measured at the cutter mounting site, they are a weak link in the structure. This is a result of their columnar structure, with the centre of

Fig. 5. The first three mode shapes corresponding to the frequencies of the wheelset: a) f1=45,1 Hz; b) f2=52,0 Hz; c) f3=74,1 Hz



gravity located high, thus decreasing the frequency of their own vibrations.

The susceptibility of the bed construction is also significant. Assuming a load on the upper part, the bed itself increases the susceptibility by ca. 50% in relation to the support (Fig. 8). The vibrations identified during operation may be forced vibrations. However, in order to take forced vibrations into consideration, their source would have to appear in the system first. It seems that the cause of such vibrations could only be the roughness of the wheelset being machined. It all points to the presence of self-excited vibrations being a result of the cutting process.

In response to the results obtained and the analysis of results of studies carried out on the actual lathe, four ways of improving the operation properties of the machine were proposed. First, the cutting parameters may be modified. However, this would result in reduced efficiency of the process and would not necessarily improve the existing situation because of the very closely situated next main own vi-



Fig. 9. Frequency response of the system to the harmonic exortion for a point at the top of the slider



Fig. 10. Displacement of a point in the lower part of the slider to force the harmonic exortion.

bration frequency of the machine. Introducing a vibration eliminator in the form of an additional mass of properly selected damping could be another solution. However, as shown by subsequent numerical analyses of the machine, this solution would not significantly change the vibration frequency, only slightly altering their amplitude (Fig. 9, Fig. 10). As a result, we remain within the resonant frequency range.

The third solution involves structural changes made to the upper part of the bed and a change of the supports' structure. This may significantly improve the machine's operating properties. However, this requires a design project, a numerical analysis of the proposed solution and a shutdown of the machine to make it available for introducing changes in its structure. The final proposal also involves an intervention in the existing structure by filling in selected body parts with polymeric concrete. As a result, we would not obtain a significant change in frequency, so the machine would continue to work in its resonance range, but we should reduce the vibration amplitude even by several times.

#### 4. Conclusions

This attempt to improve a wheelset lathe operation accuracy shows that it is a very difficult task at the exploitation stage. First, experimental research is required, e.g. an analysis of vibrations occurring during the machining. In the next step, it is necessary to develop a model and carry out some numerical analyses to obtain reference results for further analyses. With the data collected (including the machine's own frequencies and rigidity indexes) it is possible to begin structural modifications. At this stage, the possibilities are very limited and the results obtained will not always be satisfactory. Therefore, introducing a new design solution or improving the current machining parameters should be done at the design stage. This may help to reduce or avoid the machining issues described in this article.

Dynamic extortions in wheel lathes generally have low frequency as rotational speeds of spindles are in the order of 1–2 Hz. Therefore, the occurrence of vibrations in the range of several dozen Hz cannot be interpreted as forced vibration. The causes for vibrations in this range should be sought in the loss of stability, that is: the occurrence of self-excited vibrations [11, 20, 22]. Self-excited vibrations are created in closed systems (Fig. 11a, b), where apart from the mechanical system, there is also a cutting process. Their appearance depends both on the dynamic susceptibility of the mechanical system W(j $\omega$ ) and on the model of the cutting process KPS(j $\omega$ ) [9, 17, 24].

According to the Nyquist criterion, a loss of stability (which is equivalent to the occurrence of self-excited vibrations) happens when the spectral characteristics of an open system  $K_o(j\omega) = W(j\omega)$   $K_{PS}(j\omega)$  does not include point (-1, j $\omega$ ) (Fig.11c), that is, when the inequality  $K_o(j\omega) = W(j\omega) K_{PS}(j\omega) >-1$  ( $K_o(j\omega)$  characteristic is negative in the frequency range of self-excitation). Therefore, if the dynamic susceptibility of a mechanical system is high, e.g. due to low static rigidity, the stability condition may not be fulfilled and self-excited vibrations occur.



A characteristic feature of self-excited oscillations is that their frequency is close to one of the mechanical system's own vibration frequencies. If such vibrations occur, the natural way to eliminate them is a structural change which leads to a change in the self-excited vibration frequency. For an

Fig. 11. Self-excited vibrations diagram. A) B) Self-excited vibrations system C) Frequency response to stability loss

existing machine, it is practically impossible. Then there are other solutions left [1,8] which can be named as technological. They involve changes in the machining parameters, i.e. changes of  $K_{PS}(j\omega)$ .

Since the frequency of self-excited vibrations is close to one of the mechanical vibration frequencies of the mechanical system, the modal analysis allows for its identification. The classical method of determining the frequency of self-excitatory vibrations is to solve the condition Im[K<sub>o</sub>(j $\omega_0$ )] = 0, where  $\omega_0$  represents self-excited vibration

pulsation, but this method requires the knowledge of the dynamics of the cutting process  $K_{PS}(j\omega)$ .

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#### References

- 1. Altintas Y, Eynian M, Onozuka H. Identification of dynamic cutting force coefficients and chatter stability with process damping. CIRP Annals 2008; 57: 371-374, https://doi.org/10.1016/j.cirp.2008.03.048
- 2. Bąk P A, Jemielniak K. Numerical simulation of self-excited vibrations under variable cutting conditions. Journal of Machine Engineering 2015; 15 (1): 36-45.
- Bąk P A, Jemielniak K. Self-excited Vibrations Avoidance Methodology in Non-linear Numerical Simulation Environment. Procedia CIRP 2017; 62: 245-249, https://doi.org/10.1016/j.procir.2016.06.071.
- 4. Budak E, Tunc L T. Identification and modeling of process damping in turning and milling using a new approach. CIRP Annals 2010; 59: 403-408, https://doi.org/10.1016/j.cirp.2010.03.078.
- 5. Cai L, Zhang Z, Cheng Q, Liu Z, Gu PA. Geometric accuracy design method of multi-axis NC machine tool for improving machining accuracy reliability. Eksploatacja i Niezawodnosc Maintenance and Reliability 2015; 17 (1): 143-155, https://doi.org/10.17531/ein.2015.1.19.
- 6. Cui X, Chen G, Zhao J, Yan W, Ouyang H, Zhu M. Field investigation and numerical study of the rail corrugation caused by frictional selfexcited vibration. Wear 2017; 376-377 (Part B): 1919-1929.
- Ekberg A, Sotkovszki P. Anisotropy and rolling contact fatigue of railway wheels. International Journal of Fatigue 2001; 23: 29-43, https:// doi.org/10.1016/S0142-1123(00)00070-0.
- Erdbrink C D, Krzhizhanovskaya V V. Differential evolution for system identification of self-excited vibrations. Journal of Computational Science 2015; 10: 360-369, https://doi.org/10.1016/j.jocs.2015.03.004.
- Hervé B, Sinou J, Mahé H, Jézéquel L. Analysis of squeal noise and mode coupling instabilities including damping and gyroscopic effects. European Journal of Mechanics/A Solids 2008; 27 (2): 141-160, https://doi.org/10.1016/j.euromechsol.2007.05.004.
- Hiensch M, Nielsen J C O, Verheijen E. Rail corrugation in The Netherlands measurements and simulations. Wear 2002; 253: 140-149, https://doi.org/10.1016/S0043-1648(02)00093-5.
- 11. Ibrahim R A. Friction-induced vibration, chatter, squeal and chaos, part I: mechanics of contact and friction. ASME Applied Mechanics Reviews 1994; 47 (7): 227-253, https://doi.org/10.1115/1.3111080.
- 12. Jablonski A T, Barszcz T. Validation of vibration measurements for heavy duty machinery diagnostics. Mechanical Systems and Signal Processing 2013; 38 (1): 248-263, https://doi.org/10.1016/j.ymssp.2013.01.015.
- 13. Jemielniak K., Nejman M., Śniegulska-Grądzka D., Analytical and numerical determination of stability limit in turning, Journal of Machine Engineering, 2012; 17, 81-92.
- 14. Jemielniak K, Widota A. Numerical simulation of non-linear chatter vibration in turning. International Journal of Machine Tools & Manufacturing 1989; 29: 239-247, https://doi.org/10.1016/0890-6955(89)90035-7.
- Jergéus J, Odenmarck C, Lundén R, Sotkovszki P, Karlsson B, Gullers P. Full-scale railway wheel flat experiments. Procedia Institute Mechanical Engineering Part F: Journal of Rail Rapid Transit, 1999; 213: 1-13, https://doi.org/10.1243/0954409991530985.
- 16. Jin X, Wen Z. Rail corrugation formation studied with a full-scale test facility and numerical analysis. Procedia Institute Mechanical Engineering Part J: Engineering Tribology 2007; 221: 675-698, https://doi.org/10.1243/13506501JET269.
- 17. Kröger M, Neubauer M, Popp K. Experimental investigation on the avoidance of self-excited vibrations. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 2008; 366 (1866): 785-810.
- 18. Kujan K. Investigations and analysis of repeatability of geometric deviation distribution in the machining process. Eksploatacja i Niezawodnosc Maintenance and Reliability 2008; 3 (39): 45-52.
- 20. Mottershead J. Vibration and friction induced instability in disks. Shock and Vibration Digest 1998; 30 (1): 14-31, https://doi. org/10.1177/058310249803000103.
- Parida N, Das S K, Tarafder S. Failure analysis of railroad wheels and manufacturing aspects, Engineering Failure Analysis 2009; 16: 1454-1460, https://doi.org/10.1016/j.engfailanal.2008.09.021.
- 22. Rusinek R, Warmiński J, Szabelski K, Teter A, Litak G, Lipski J, Zaleski K. Influence of changeable parameters of straight turning on final surface quality. Eksploatacja i Niezawodnosc Maintenance and Reliability 2001; 5 (12): 41-42.
- 23. Sheng X, Thompson D J, Jones C J C, Xie G, Iwnicki S D, Allen P, Hsu S S. Simulations of roughness initiation and growth on railway rails. Journal of Sound and Vibration 2006; 293: 819-829, https://doi.org/10.1016/j.jsv.2005.08.050.
- 24. Spelsberg-Korspeter G. Structural optimization for the avoidance of self-excited vibrations based on analytical models. Journal of Sound and Vibration 2010; 329: 4829-4840, https://doi.org/10.1016/j.jsv.2010.04.004.
- 25. Stone D H, Carpenter G F. Wheel thermal damage limits, railroad conference. Procedia of the 1994 ASME/IEEE Joint, 1994.
- 26. Uriarte L, Zatarain M, Axinte D, Yagüe-Fabra J, Ihlenfeldt S, Eguia J, Olarra A. Machine tools for large parts. CIRP Annals Manufacturing Technology 2013; 62 (2): 731-750.
- 27. Urbikain G, Campa F-J, Zulaika J J, López de Lacalle L N, Alonso M A, Collado V. Preventing chatter vibrations in heavy-duty turning operations in large horizontal lathes. Journal of Sound and Vibration 2015; 340: 317-330, https://doi.org/10.1016/j.jsv.2014.12.002.
- 28. Vaičiūnas G, Bureika G, Steišūnas S. Research on metal fatigue of rail vehicle wheel considering the wear intensity of rolling surface. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (1): 24–29, http://dx.doi.org/10.17531/ein.2018.1.4.

- 29. Vaičiūnas G., Lingaitis L.P., The influence of railroad curves the wear of lubricated and unlubricated wheel flanges. Eksploatacja i Niezawodnosc Maintenance and Reliability 2010; 3 (47): 40–43.
- Wąsik M, Kolka A. Machining Accuracy Improvement by Compensation of Machine and Workpiece Deformation. Procedia Manufacturing 2017; 11: 2187-2194.

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#### Leon PROCHOWSKI

#### EVALUATION OF THE PROCESS OF MILEAGE GROWTH DURING THE OPERATION OF MOTOR TRUCKS, IN SEVERAL CATEGORIES OF ENGINE CUBIC CAPACITY

#### OCENA PROCESU NARASTANIA PRZEBIEGU PODCZAS EKSPLOATACJI SAMO-CHODÓW CIĘŻAROWYCH W KILKU KATEGORIACH POJEMNOŚCI SILNIKA\*

The intensity of use of motor vehicles and the range of the transport jobs performed change during the many-year operation of such vehicles. The changes are introduced in result of ongoing analyses of actual current vehicle operation costs, reliability, and performance characteristics. The changes in the vehicle operation process, taking place with vehicle's age, were analysed on the grounds of the mileage of over 9 000 motor trucks. The analysis covered a 20-year period of vehicle operation. The analysis results were used to estimate the mathematical models that describe the basic characteristics of the mileage growth process, with changes in these characteristics as observed in the recent years along with an intensive development of the road transport in Poland. Models of vehicle mileage growth have been developed for seven categories of engine cubic capacity. The coefficients of model equations have been given and the accuracy of the mileage values calculated on these grounds has been comprehensively evaluated. The relative measures of the scatter in the mileage values obtained from these models do not exceed 12 % of the average values determined from experimental data. A procedure has been proposed that leads to evaluating the mileage growth process is strongly related to the engine cubic capacity. The mileage growth process is an important source of information for the planning of vehicle operation of the vehicle of the scatter of the mileage growth process is an important source of information for the planning of vehicle operation of the engine cubic capacity. The mileage growth process is an important source of information for the planning of vehicle operation of the scatter of the mileage growth process is an important source of information for the planning of vehicle operation of the scatter of the mileage growth process is an important source of information for the planning of vehicle operation of motor vehicles by transport companies.

Keywords: motor vehicle mileage, motor vehicle operation, motor trucks, estimation of motor vehicle mileage.

W czasie wieloletniej eksploatacji samochodów zmianie ulega intensywność ich użytkowania oraz zakres realizowanych zadań transportowych. Zmiany te są rezultatem analizy kosztów eksploatacji, niezawodności oraz osiąganych parametrów trakcyjnych. Zmiany w procesie eksploatacji, które zachodzą wraz z wiekiem samochodów, analizowano na podstawie przebiegu prawie 9000 samochodów ciężarowych. Analizowany jest dwudziestoletni okres eksploatacji pojazdów. Rezultaty tej analizy wykorzystano podczas estymacji modeli matematycznych, które opisują zasadnicze cechy procesu narastania wartości przebiegu, pojawiające się w ostatnich latach wraz z intensywnym wzrostem transportu drogowego w Polsce. Opracowano modele narastania przebiegu w siedmiu kategoriach pojemności silnika. Podano współczynniki równań tych modeli oraz dokonano wszechstronnej oceny do-kładności obliczonych na ich podstawie wartości przebiegu. Obliczone względne miary rozrzutu wartości przebiegu z tych modeli nie przekraczają 12% od wartości średnich, wyznaczonych z danych eksperymentalnych. Zaproponowano procedurę postępowania, która prowadzi do wyznaczenia oceny procesu narastania przebiegu i jest oparta na dotychczasowych doświadczeniach w tym zakresie. Pokazano, że proces narastania przebiegu ma silny związek z pojemnością silnika. Proces narastania przebiegu jest ważnym źródłem informacji podczas planowania eksploatacji pojazdów, prognozowania kosztów, a także oceny emisji spalin i zużycia energii w całym cyklu eksploatacji samochodów w firmach transportowych.

*Słowa kluczowe*: przebieg samochodów, eksploatacja samochodów, samochody ciężarowe, ocena przebiegu samochodów.

### 1. Introduction and analysis of the current state of knowledge in this field

Motor trucks are selected according to the transport tasks planned. There are many factors of considerable importance for the vehicle selection, such as load capacity, unladen mass, fuel consumption, or engine cubic capacity. They are interrelated, e.g. the engine capacity has an impact on the power output and fuel consumption. During the many-year operation of motor vehicles, changes take place in the intensity of use of such vehicles and in the range of the transport jobs performed. The intensity of vehicle use is chiefly measured by the rate of growth in vehicle mileage. The vehicle mileage values constitute a basis for vehicle operation planning and cost forecasting. The vehicle mileage is taken into account in various ways to estimate e.g. insurance risk [6, 15], exhaust emissions [1, 5, 12, 27], or costs of fuel, tyres, or spare parts [16, 23]. The publications concerning this subject matter are predominantly dedicated to the intensity of use of motor cars [5, 6, 9, 12, 23]. However, the average annual mileage of heavy goods vehicles (HGV) is many times as high as that of motor cars (MC). As an example, the HGV to MC mileage ratio reported for the UK in 2006 exceeded 3.5 [25]. Moreover, the intensity of MC operation has been recently decreasing [13, 20].

In Poland, a high rate of growth in the motor truck traffic is now observed [14]. The mileage of motor trucks with up to 3 500 kg (3.5 t) gross vehicle mass (GVM) is often compared with that of motor cars [23, 26]. The light motor trucks, popularly referred to as local transport vehicles (LTV) or light commercial vehicles (LCV), are chiefly used for distribution-type jobs. According to catalogues [7],

<sup>(\*)</sup> Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

the mileage of motor trucks with up to 3.5 t GVM, after 10 years in service, exceeds that of motor cars with comparable engine cubic capacity by 30 %. By contrast, the mileage values for HGVs (with GVM exceeding 3.5 t) are higher than those for motor cars are by more than 300 %. Increasingly often attention is paid to the negative effects of road transport, which include the external costs such as exhaust emission effects and high fatality of road accidents [4, 18]. In the UK, the number of fatal accidents with HGV drivers is 1.8 per 100 million km and it is twice as high as that with motor car drivers [2]. The high intensity of motor truck operation determines the rate of replacement of the fleet of such vehicles in Poland. In consequence, the motor trucks aged up to 5 years perform 49.5 % of cargo transport jobs (in tonkilometres) and those aged up to 10 years carry out as much as 82.4 % of such jobs [22, 24]. Motor trucks having been operated for more than 20 years are rarely seen on roads and their share in the transport work is 0.5 % [19].

The objective of this work is to evaluate the process of growth in the mileage of motor trucks with successive years of the vehicles being in service. The evaluation will be based on indicators related to several measures of the deviations of model data from empirical data. The problem will be analysed in connection with the engine cubic capacity value. The models having been developed will facilitate the analysis of the mileage growth rate, recognition of the major tendencies, and identification of the development trends in the successive periods of vehicle operation. The models of the mileage growth process are often the main source of information in the prognostic calculations of the trends to develop and of the values of the indicators that help to manage the operation of a motor vehicle fleet. The research conducted in this field provides anticipating information about vehicles' mileage growth, rate of approaching the planned or target mileage, current advancement in reaching this mileage and the maximum time of cost-effective vehicle use, termination of the vehicle use, replacement of vehicle fleet, or modifications to the operation of the fleet [3, 10, 11, 21].

This work consists of several successive stages, which include analysis of data and estimation of the models and model accuracy. Detailed and current data about the intensity of operation of motor trucks (i.e. HGVs and LTVs), based on a large dataset, are not easily available. There is a lack of data about the LTV mileage growth process and about the relation between this process and the engine cubic capacity. There is also a lack of current information how the increasing number and diversity of motor trucks influenced the intensity of operation of such vehicles in Poland.

#### 2. Characterization of the dataset

The information about motor vehicles and their mileage was collected on the grounds of:

- surveys carried out among motor truck drivers;
- information about vehicles' mileage and characteristics recorded during mandatory periodical inspections carried out at Vehicle Testing Stations (VTS);
- analysis of post-accident motor truck inspection records.

Apart from other information, the dataset includes basic technical data of the vehicle, date of first registration, and mileage covered in Poland. The data concerning special motor vehicles and vehicles with load capacity below 500 kg as well as vehicles with monthly mileage values below 100 km/m and above 25 000 km/m were excluded from the dataset; the upper limit was adopted because in practice the very high monthly mileage values are hardly achievable in the conditions of road traffic in Poland. The vehicle models that predominated in the dataset have been specified in Tables 1a and 1b.

Note: The GVM and engine cubic capacity values have been confirmed in catalogues [7].

In the dataset, the same vehicle makes can be seen that predominate in numerical summaries of the first registrations in Poland. For example: Citroen, Fiat, Ford, Mercedes-Benz, Peugeot, Renault, and Volkswagen predominate in the set of local transport vehicles. The same vehicle makes have been indicated as predominating among the first registrations of LTVs in the Automotive Industry Reports of 2008, 2014, and 2016 [22]. In the group of vehicles with GVM exceeding 3.5 tons (metric), DAF, Iveco, MAN, Mercedes-Benz, Renault Trucks, Scania, and Volvo Trucks are the makes that predominate in the number of HGV sales in the Polish market and in the number of first registrations of such vehicles [22]. The same makes predominate in Table 1b.

#### 3. Procedure of evaluation of the mileage growth process

Very wide scatter can be observed in the motor truck mileage values after vehicle operation periods of the same duration. This scatter results from very diverse transport jobs performed and from variations in the intensity of vehicle operation. This characteristic feature of the motor truck mileage is confirmed by multiannual statistics. For illustration: the average annual mileage of such vehicles in the UK has been determined as 79 000 km with a standard deviation of 63 000 km, according to [17].

To find a relatively representative image of the process of growth in the motor truck mileage in Poland with taking into account the

Engine cubic capacity category [cm <sup>3</sup> ]	Vehicle makes and models	GVM [tons (metric)]	Example engine ca- pacity values [cm <sup>3</sup> ]
Up to 1 499	Citroen Berlingo 1.4; Fiat Doblo Cargo; Opel Combo CDTI; Peugeot Part- ner 1.4; Renault Kangoo Express III dCi; Volkswagen Caddy 1.4, Caddy Maxi	1.6; 1.7; 1.9; 2.2; 2.3; 2.4	1 197; 1 248; 1 360; 1 390; 1 461
1 500-1 999	Citroen Berlingo 1.9D, Berlingo II 1.6 HDI; Fiat Doblo Cargo JTD; Ford FT280; Opel Combo Diesel, Combo 1.7D, Vivaro CDTI; Peugeot Part- ner II HDI; Renault Kangoo D, Trafic DCI; Volkswagen Caddy 1.9SDI, Trans- porter T5 TDI	1.6; 1.8; 1.9; 2.0; 2.2; 2.7; 3.0	1 560; 1 686; 1 868; 1 870; 1 896; 1 910; 1 968; 1 995; 1 999
2 000-2 499	Citroen Jumper 35HDI; Fiat Ducato 30MJ; Ford FT 350 TDCi, Transit; Mercedes Sprinter 208,, 313, Vito 110, 115; Opel Vivaro CDTI; Peu- geot Boxer 335 HDI; Renault Master dCi, TD,Trafic dCi; Volkswagen Trans- porter T4 SD	2.6; 2.7; 2.8; 2.9; 3.0; 3.1; 3.5	2 148; 2 151; 2 163; 2 198; 2 299; 2 370; 2 402; 2 464;
2 500-2 999	Fiat Ducato 10, Maxi 35 MJ; Iveco Daily 35 C, 35; Mercedes Sprint- er 210, Vito CDI; Peugeot Boxer 435 HDI; Renault Master Maxi	2.8; 2.9; 3.5	2 798; 2 800; 2 874; 2 953; 2 987; 2 998

Table 1a. Motor trucks belonging to the group of  $GVM \le 3.5$  t

Engine cubic capacity category [cm <sup>3</sup> ]	Vehicle makes and models	GVM [tons (metric)]	Example engine ca- pacity values [cm³]
2 500-9 999	Iveco Eurocargo, Stralis ML, ML180; MAN M2000, TGL; Mer- cedes-Benz 508D, 515 CDI , Sprinter, 814, 11141320, Atego; Volvo FL, FE, FM	4.6; 5.0; 6.0; 7.5; 8.0; 8.6; 10.0; 12.0; 13.0; 16; 18.0; 20.0	2 874; 3 908, 3 920; 4 249; 4 250; 4 580; 5 880; 5 958; 6 374; 6 871; 7 146; 9 364; 9 603
10 000-11 999	MAN TGA, TGX, TGS; Mercedes Benz Actros, Axor; Renault Pre- mium, Premium Route; Scania 114, 124, R380, 124/420, 124/4 70, R420; R480;	18.0; 18.6; 19.0; 25.0; 26.0	10 300; 10 308; 10 318; 10 518; 10 520; 10 600; 10 635; 10 640; 10 837; 11 100; 11 116; 11 700; 11 705; 11 946; 11967
12 000+	DAF XF95, XF105; Iveco Stralis; MAN F2000, TG, TGA; Renault Magnum; Scania R440, R480, G440; Vol- vo FH12, FH16, FH400, FH440, FH480, FH500	18.0; 18.1; 18.6; 19.0; 26.0	12 100; 12 130; 12 771; 12 777; 12 780; 12 580; 12 740; 12 777; 12 780; 12 816; 12 880; 12 882; 12 895; 12 902

Table 1b. Motor trucks belonging to the group of GVM > 3.5 t

above as well as the results of the calculations carried out previously [19], a procedure consisting of the following stages was prepared:

- data collection;
- analysis of the data, with dividing the dataset into subsets;
- estimation of the average mileage values with determining the coefficient of variation;
- removal of outliers;
- approximation of the relation between the mileage and the vehicle operation time;
- estimation of the mileage growth models;
- evaluation of the accuracy of the estimators determined for the mileage growth models.

In the calculations, the following notation was adopted for the basic quantities:

- $L_i$  mileage covered by the *i*<sup>th</sup> vehicle during time  $t_i$ ;
- $L_{10}, L_{20}$  -total vehicle mileage after 10 and 20 years of vehicle operation, respectively;
- X, M, Q arithmetic mean, median, and quantile, respectively;
- S standard deviation;
- *W* relative coefficient of variation;
- $R, \varphi$  coefficient of determination and fraction of variance unexplained (FVU), respectively.

The scope of the work done at individual stages of the procedure, denoted by A1, A2, etc., has been described below.

A1. The data collection stage pertains to the motor trucks that are currently participating in the road cargo transport. In result of this stage, a representative dataset should be obtained that would include at least the technical specifications, mileage, and period of operation of individual vehicles. At this stage, it is important that various information sources should be used for the dataset formed to be representative.

A2. The analysis of the data collected should make it possible to clear the dataset, in a reasonable way, of the data that might adversely affect the calculation results, e.g. to remove the data of motor cars and car-based vehicles, which may be registered in Poland as accepted for cargo transport (or, more precisely, as passenger/cargo vehicles). At this stage, certain subsets are separated, which consist of uniform-category vehicles (e.g. vehicles for local, interurban, or international

transport). The vehicles of individual categories are used for different transport jobs, which have an impact on the vehicle mileage. The division of a dataset depends on the dataset size and on the exact objective of the calculations.

The data analysis was based on an assumption made that it would cover a 20-year period of vehicle operation and the distance travelled by the end of such a period was referred to as "target mileage" (expressed in kilometres). The vehicles that were operated within this period for less than 3 months or that were more than 242 months old were not taken into account. The vehicles operated for only the first two months of the period under analysis were ignored because of very wide scatter in the values of the mileage covered by them during that time.

At this stage, the motor trucks of each category were divided into n subgroups. The vehicles whose operation time  $t_i$  was within the interval:

$$T_k < t_i \le T_{k+1} \tag{1}$$

were counted in the  $k^{\text{th}}$  subgroup. The limits of disjoint time intervals were defined with a monthly step, i.e.:

$$T_k = 12(k-1)$$
 for k = 2, 3, ..., n (2)

and, additionally,  $T_1 = 2$  months and  $T_{21} = 242$  months. (3)

The separation of subgroups in which the numbers of vehicles would be adequate for research purposes (i.e. would be not less than a required minimum denoted by  $m_0$ ) makes a basis for further calculations. In many cases, vehicles are divided into subgroups that cover successive vehicle operation periods whose length is  $T_0 = 12$  months.

**A3.** At the stage of estimation of the average mileage values in individual subgroups, the scope of calculations was defined with taking into account, *inter alia*, the following premises:

 the arithmetic mean is an estimator rather insusceptible to an error in the evaluation of the properties of a dataset but it is susceptible to outliers (extreme values).

- the median is rather insusceptible to outliers, but it is unsuitable for statistical calculations.
- the average monthly mileage value calculated by dividing the total mileage value by the number of months of the vehicle operation period is burdened with an error arising from changes in the mileage growth rate with vehicle operation time.

In each subgroup, the vehicle mileage L was treated as a random variable and  $L_i$  was the  $i^{\text{th}}$  value of this variable. In the  $k^{\text{th}}$  subgroup that consisted of  $m \ge m_0$  vehicles, the following operations were carried out:

B1. Forming of a series of mileage values  $L_{0k}$  { $L_1$ ,..., $L_i$ ,..., $L_m$ } consisting of *m* members arranged in ascending order.

B2. Calculation of the estimators: arithmetic mean  $X_{0k}$  ( $\tau_k$ ), median  $M_{0k}$  ( $\tau_k$ ), quantiles  $Q_{1k}$  ( $\tau_k$ ) and  $Q_{3k}$  ( $\tau_k$ ), and relative coefficient of variation  $W_{0k}$  ( $\tau$ ) as the following quotient:

$$W_{0k} = \frac{S_{0k}}{X_{0k}} \tag{4}$$

where  $S_{0k}$  is standard deviation,  $\tau_k$  is the central value of the vehicle operation period in the  $k^{\text{th}}$  subgroup, and  $Q_{1k}(\tau_k)$  and  $Q_{3k}(\tau_k)$  are the lower and upper quantile, respectively.

In result of these calculations, the following series of discrete values were obtained for every vehicle category:

$$X_0\{X_{0k}(\tau_k), k = 1, 2, ..., n\}, M_0\{M_{0k}(\tau_k), k = 1, 2, ..., n\}, W_0\{W_{0k}(\tau_k), k = 1, 2, ..., n\}$$
(5)

A4. Results of the calculations carried out at stage A3 make it possible to estimate the coefficient of mileage variation, the value of which shows whether the removal of outliers is necessary. High  $W_{0k}$  values indicate excessive scatter in the mileage values in the  $k^{th}$  subgroup. If the scatter is wide, the average mileage value in a specific subgroup not always adequately characterizes the mean mileage level. In such a case, efforts should be made to reduce the impact of the values that most differ from the average in the subgroup on the results of further calculations. The steps of this kind taken in the  $k^{th}$  subgroup may be divided into two sub-stages. At the first one, a series denoted by  $L_{Ek}$  was formed by removing 10 % of the first and last members of  $L_{0k}$ , i.e. the lowest and highest mileage values. Thus, the  $L_{Ek}$  series consisted of  $m - 2m_E$  members, i.e.

$$L_{Ek} \{ L_{m_F+1}, L_{m_F+2}, \dots, L_{m-m_F} \}, m_E = E(0.1m)$$
(6)

where operator E has the meaning of rounding off to the nearest integer.

At the second sub-stage, a series denoted by  $L_{Qk}$  was formed by clearing  $L_{0k}$  of the members where the  $L_i$  values were covered by the criterion:

$$L_i \le Q_{1k} \text{ or } L_i \ge Q_{3k} \tag{7}$$

Following this operation, the  $L_{Qk}$  series consisted of members situated centrally in  $L_{0k}$  and falling within the range  $Q_{1k} < L_i < Q_{3k}$ .

After the removal of the outlying mileage values, the numbers of vehicles in individual subgroups decreases. In consequence, the numbers of vehicles in some subgroups may become  $m < m_0$ . If the  $k^{\text{th}}$  subgroup consists of less than  $m_0$  vehicles, it should be merged with subgroup k+1. The subgroup thus combined will consist of vehicles whose operation time would fall within the interval:

$$T_k < t_i \le T_{k+2},\tag{8}$$

which is twice as wide as those considered previously.

Therefore, an operation was carried out to reduce the width of such "double" intervals to  $T_0$  months with maintaining the natural scatter in the vehicle mileage values. With this objective in view, the mean mileage value  $X_{(k)}$  and the central value of the vehicle operation time  $\tau_{(k)}$  for the combined subgroup was calculated. Now, the  $X_{(k)}$  and  $\tau_{(k)}$  values were used to determine the deviation of the monthly mileage  $(PM_i)$  for the *i*<sup>th</sup> vehicle of the subgroups combined together:

$$PM_{i} = \frac{L_{i} - X_{(k)}}{t_{i} - \tau_{(k)}}$$
(9)

For the vehicles where  $|t_i - \tau_{(k)}| \ge 0.5T_0$  (i.e. whose operation time was longer or shorter than  $\tau_{(k)}$  by more than  $0.5T_0$  months), a reduced mileage value  $L_{(i)}$  and a reduced vehicle operation time  $t_{(i)}$  were calculated as follows:

$$L_{(i)} = L_i + 0.5PM_i \left( t_i - \tau_{(k)} \right) \tag{10}$$

$$_{(i)} = t_i + 0.5(t_i - \tau_{(k)}) \tag{11}$$

In result of the above calculations, new parameters denoted by  $L_{(i)}$  and  $t_{(i)}$  were obtained for the *i*<sup>th</sup> vehicle. They were substituted for the parameters  $L_i$  and  $t_i$  used previously and they already fell within the time interval:

$$\tau_{(k)} - 0.5T_0 < t_{(i)} \le \tau_{(k)} + 0.5T_0 \tag{12}$$

The new subgroup, formed by merger of subgroups k and k+1, has characteristics similar to those of the subgroups that consisted of at least  $m_0$  vehicles when they were initially defined. After these calculations, the diversity of the vehicle mileage and operation time values remained close to that recorded originally, although the said values were reduced to fall within the interval as defined by (12). The diversity of the mileage values  $L_i$  must be maintained in the subgroup merging process for the same procedure, with two sub-stages of removing the mileage outliers, to remain applicable when forming the  $L_{Ek}$  and  $L_{Ok}$  series.

The values of members of the  $L_{Ek}$  and  $L_{Qk}$  series were used to determine series of the following discrete values for each vehicle category:

$$X_{E,O}\{X_{Ek,Ok}(\tau_k), k = 1, 2, ..., n_0\}$$
(13)

where:  $X_{E,Q}$  represents series  $X_E$  and  $X_Q$ , respectively, and  $n_0 < n$  in result of the merger of some subgroups.

A5. At this stage, a transition takes place from the series of discrete averaged values  $M_0$ ,  $X_E$ , and  $X_Q$  in vehicle subgroups to a continuous function. This is done by approximating the dependence of the averaged vehicle mileage values on the vehicle operation time. In this work, the approximation was based on regression lines. In result of the approximation process, continuous functions in the form as follows were obtained, describing the vehicle mileage growth with vehicle operation time:

$$\hat{y}_a = f_a(\tau) \tag{14}$$

In consideration of the properties of the process of approximation based on regression lines, including strong dependence of the course of such lines on the degree of the approximating polynomial and on the number of the data available and on their nature, the approximating functions were determined in two ways:

- by using models with a  $3^{rd}$  degree polynomial based on three series, i.e.  $M_0, X_E$ , and  $X_O$ , the following was calculated:

$$\hat{y}_{E,Q,M} = f_{E,Q,M}(\tau);$$
 (15)

- by selecting models with  $2^{nd}$  and  $4^{th}$  degree polynomials based on the  $X_Q$  series of values, the following was obtained:

$$\hat{y}_{W2,W4} = f_{W2,W4}(\tau) \tag{16}$$

where subscripts  $_{W2}$  and  $_{W4}$  correspond to the degree of the polynomial.

In total, five approximating functions were calculated for each vehicle category.

A6. The estimation of the vehicle mileage growth models so that they were burdened with the smallest possible error was based on the combined use of approximating functions (15) and (16) for determining averaged functions on these grounds. The method of moving average was used to calculate the values:

$$Y_A(\tau), k = 1, 2, ..., n_0$$

that provided a basis for the estimation of the averaged approximating function:

$$\hat{y}_A = f_A(\tau) \tag{17}$$

The averaged approximating function (17) was treated as an estimator of the mileage growth model prepared for motor trucks.

**A7.** The evaluation of the accuracy of this estimator was based on absolute and relative indicators. The following absolute indicators were used (based on [8, 28]):

- standard error of estimation:

$$S_{E,Q,M} = \sqrt{\frac{1}{n_0 - z - 1} \sum_{k=1}^{n_0} e_{Ek,Qk,Mk}^2}$$
(18)

where:  $e_{Ek,Qk,Mk} = y_{Ek,Qk,Mk} - \hat{y}_{Ak}$ ;  $y_{Ek,Qk,Mk}$  – empirical values, i.e. the  $k^{\text{th}}$  members of series  $X_E$ ,  $X_Q$ , and  $M_0$ , respectively;  $\hat{y}_{Ak}$  – mileage value obtained from model (17); z – number of explanatory variables in the model;

- mean absolute error:

$$\overline{X}_{E,Q,M} = \frac{1}{n_0} \sum_{k=1}^{n_0} \left| e_{Ek,Qk,Mk} \right|$$
(19)

The relative indicators used included:

- coefficient of determination related to the values of  $X_E, X_Q$ , and  $M_0$ , i.e.

$$R_{E,Q,M}^{2} = \frac{\sum_{k=1}^{n_{0}} (\hat{y}_{Ak} - \overline{y}_{E,Q,M})^{2}}{\sum_{k=1}^{n_{0}} (y_{Ek,Qk.Mk} - \overline{y}_{E,Q,M})^{2}}$$
(20)

- coefficient of variation in the error of estimation:

$$V_{E,Q,M} = \frac{S_{E,Q,M}}{\overline{y}_{E,Q,M}} 100\%$$
(21)

where:  $\overline{y}_{E,Q,M}$  – average value of series  $X_E$ ,  $X_Q$ , and  $M_0$ , respectively;

- fraction of variance unexplained (FVU):

$$\phi_{E,Q,M}^{2} = \frac{\sum_{k=1}^{n_{0}} (y_{Ek,Qk,Mk} - \hat{y}_{Ak})^{2}}{\sum_{k=1}^{n_{0}} (y_{Ek,Qk,Mk} - \overline{y}_{E,Q,M})^{2}}$$
(22)

The symbol  $S_{E,Q,M}$  covers three quantities, i.e.  $S_E$ ,  $S_Q$ , and  $S_M$ , which are calculated from  $X_E$ ,  $X_Q$ , or  $M_0$ , as appropriate. The same subscripts have been used in equations (18)-(22).

The determination of the estimator evaluation indicators is the final step of the procedure, which was followed in practice at the evaluation of the process of growth in the motor truck mileage during the 20-year vehicle operation period.

#### 4. Example implementation of the procedure developed

At the initial data collection stage, the vehicles were divided into two groups, based on the GVM value, i.e. up to and above 3.5 tons (metric). Thus, two separate datasets were formed, which covered 5 084 vehicles of the first group and 3 855 vehicles of the other one. The distribution of the number of vehicles, by age, in both groups has been shown in Fig. 1. Both in the dataset and in the real road cargo transport, the vehicles having been operated for up to 10 years predominate.





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Fig. 2. Engine power output vs cubic capacity curves characterizing the datasets

Fig. 2 supplements the information about the vehicles under analysis that has been provided in Table 1. It shows that the engine capacity values gather in a few major ranges: 1 850-1 999, 2 400-2 499, 2 800-2 999, 5 900-6 900, 10 000-11 999, and 12 000-13 000 cm<sup>3</sup>; in this study, therefore, this finding has been adopted as a basis for vehicle categorization.



Fig. 3. Numbers of vehicles within successive ranges of engine cubic capacity

In Fig. 3, the engine cubic capacity values have been grouped in ranges of up to 1 000 cm<sup>3</sup>, 1 001-1 200 cm<sup>3</sup>, and so on. In consideration of the above, the distribution of engine capacity values as shown in Fig. 2, and classification adopted in [22, 24], the vehicles under analysis have been divided into engine capacity categories as follows:

- four categories in the group of local transport (delivery) vehicles (LTV);
- three categories in the group of heavy goods vehicles (HGV, with more than 3.5 metric tons GVM).

The limits of individual engine capacity categories and percentage of vehicles of individual categories in both groups have been presented in Table 2.

In each category, the vehicles were divided into n = 20 subgroups, based on the vehicle operation time, which was determined with 1 month accuracy, according to (1)-(3). The subgroups varied in size, with 63 vehicles per subgroup, on average, in the group of vehicles with GVM of up to 3.5 t and 64 vehicles per subgroup, on average, in the group of vehicles with GVM of above 3.5 t. The first subgroup consisted of vehicles whose operation time ranged from 3 months to 12 months; in the other one, there were vehicles having been operated for 13-24 months. When forming the subgroups, an assumption was made that a subgroup should consist of not less than  $m_0 = 20$  vehicles. However, there were more than 10 subgroups where the number of vehicles remained below this minimum, in spite of a long data collection time (3 years). For these subgroups, the calculations to be done at stage A3 were not carried out. Only when these subgroups were merged with the next ones (at stage A4), the data about the vehicles of these subgroups were taken for further computations.

In the subgroups, the estimators of arithmetic mean  $X_{0k}$  ( $\tau_k$ ), median  $M_{0k}$  ( $\tau_k$ ), quantiles  $Q_{1k}$  ( $\tau_k$ ) and  $Q_{3k}$  ( $\tau_k$ ), and relative coefficient of variation  $W_{0k}$  ( $\tau_k$ ) were calculated. Example results of calculations carried out for the subgroups of vehicles belonging to category S02 have been presented in Fig. 4. Gradual growth in  $X_{0k}$  and  $M_{0k}$  with increasing  $\tau_k$  as well as high values of the coefficient of variation  $W_{0k}$ 

can be seen in the graphs.

High values of the relative coefficient of variation (W > 0.4) can be seen in Fig. 4 and for many vehicle subgroups, especially for  $k \le 4$ . This shows that the average value not always adequately characterizes the mean mileage level. Therefore, 10 % of the first and last members were removed at stage A4 from  $L_{0k}$  in the subgroups and thus the  $L_{Ek}$  series were formed. Then, on the grounds of results of calculation of quantiles  $Q_{1k}$  ( $\tau_k$ ) and  $Q_{3k}$  ( $\tau_k$ ), the  $L_{0k}$  series were cleared of the vehicles whose mileage was covered by the following criterion:

#### $L_i \leq Q_{1k}$ or $L_i \geq Q_{3k}$

In result of the above, the series  $L_{Ek}$  and  $L_{Qk}$  of mileage values were formed, whose members were situated centrally in  $L_{0k}$ .

When these operations were completed, all the  $20 \times 7 = 140$  subgroups under analysis included 37 ones with m < 20 (i.e. which consisted of less than 20 vehicles). Therefore, the undersized subgroups were merged with the next ones. The new series of mileage values  $L_{Ek}$  and  $L_{Qk}$  were used for determining discrete estimator values, based on (4) and (13), i.e.:

Engine cubic capacity [cm³], GVM ≤ 3.5 t	Vehicle category symbol	Percentage [%] in the group of GVM ≤ 3.5 t	Engine cubic capacity [cm³], GVM > 3.5 t	Vehicle category symbol	Percentage [%] in the group of GVM > 3.5 t
Up to 1 499	S01	13.0	2 500-9 999	S2	14.1
1 500-1 999	S02	28.6	10 000-11 999	S10	46.3
2 000-2 499	S03	45.4	12 000 and more	S12	39.6
2 500-2 999	S04	13.0	-	-	-

Table 2. Limits of individual engine capacity categories [cm<sup>3</sup>] and percentage of vehicles of individual categories in both groups

Table 3. Values of the mileage and coefficient of variation for a few values of  $\tau_k$ 

Vehicle category: S02							
Years of vehicle operation, $ au_k$	$X_{0k}$ [km]	$X_{Ek}$ [km]	$X_{Qk}$ [km]	W <sub>0k</sub>	$W_{Ek}$	$W_{Qk}$	
2.5	75 120	68 320	68 320	0.627	0.403	0.242	
8.5	212 850	207 140	202 930	0.422	0.261	0.123	
16.0	265 190	256 870	256 780	0.401	0.207	0.121	
Target mileage, L <sub>20</sub>	298 000	285 000	284 000	0.454*	0.294*	0.169*	
	Vehicl	e category: S12					
Years of vehicle operation, $ au_k$	$X_{0k}$ [km]	$X_{Ek}$ [km]	$X_{Qk}$ [km]	W <sub>0k</sub>	$W_{Ek}$	$W_{Qk}$	
2.5	202 540	205 360	209 380	0.435	0.289	0.153	
8.5	870 360	882 180	883 440	0.243	0.152	0.075	
15.0	1 009 120	1 002 240	1 007 810	0.205	0.056	0.036	
Target mileage, L <sub>20</sub>	1 390 000	1 310 000	1 255 000	0.351*	0.198*	0.118*	

\* Average values of coefficient W, calculated for 20 years of vehicle operation; the  $L_{20}$  values were calculated from the approximating functions  $\hat{y}$  according to (15).

W



Fig. 4. Results of calculations of the  $X_{0k}$ ,  $M_{0k}$ , and  $W_{0k}$  values in the subgroups of vehicles belonging to category S02

 $X_{E,O}\{X_{Ek,Ok}(\tau_k), k = 1, 2, ..., n_0\}, W_{E,O}\{W_{Ek,Ok}(\tau_k), k = 1, 2, ..., n_0\}$ 

$$W_{Ek} = \frac{S_{Ek}}{X_{Ek}} , \quad W_{Qk} = \frac{S_{Qk}}{X_{Qk}}$$

 $S_{Ek}$  and  $S_{Qk}$  are standard deviations and  $W_E$  and  $W_Q$  are coefficients of variation in mileage values in series  $L_{Ek}$  and  $L_{Qk}$ .

Examples of the calculation results have been presented in Table 3.

These calculation results were used to evaluate the effectiveness of the outliers-removal operation. Attention was paid to the impact of the outliers-removal operation used on the average mileage values in individual subgroups and on the values of the coefficient of variation. The  $X_{0k}$ ,  $X_{Ek}$ , and  $X_{Qk}$  values in Table 3 do not differ very much from each other. They insignificantly changed with the removal of outliers in individual subgroups, in particular:

- $-X_{0k} > X_{Ek} > X_{Qk}$ , when the average values were chiefly affected by very high mileage values  $L_i$ ;
- $-X_{0k} < X_{Ek} < X_{Qk}$ , when a predominating impact was exerted by very low values  $L_i$ .

An analysis of values  $W\{W_0, W_E, W_Q\}$ , based on calculation results obtained for all the vehicle categories, revealed beneficial effects of the removal of outliers from  $L_E$  and  $L_Q$ . This is confirmed by the  $W_E$  and  $W_Q$  values being definitely lower than  $W_0$  (see Table 3). Desirable effects of the outliers-removal operation has also been illustrated in Fig. 5 by the relations between the extreme  $L_i$  values in series  $L_0$ ,  $L_E$ , and  $L_Q$  and the  $X_{0k}$ ,  $X_{Ek}$ , and  $X_{Qk}$  values. The calculation results have been presented in percentage terms, where the average values in individual subsets were assumed as 100 %.

Fig. 6 shows example curves representing the approximating functions determined according to (15) and (16). Figs 6a and 6c shows values  $X_{Ek}$ ,  $X_{Qk}$ , and  $M_{0k}$  (points in the graphs) and the functions that approximate the mileage growth process for vehicles of categories S03 and S12, based on models with a 3<sup>rd</sup> degree polynomial and marked



Fig. 5. Extreme (MIN and MAX) and mean mileage values in series  $L_0$ ,  $L_E$ , and  $L_Q$ , calculated for the S02 category vehicles (in percentage terms) and compared with each other for  $\tau_k = 2.5$ , 10.5, and 18.0 years of vehicle operation

Polynomial XE, Polynomial XQ, and Polynomial M0, respectively. In Figs 6b and 6d, the  $X_{Qk}$  values and the approximating functions based on models with  $2^{nd}$  and  $4^{th}$  degree polynomials and marked as *Polynomial XQ2* and *Polynomial XQ4*, respectively, have been presented.

In result of an analysis of the approximating functions, the following findings have been formulated:

- The comparison of the approximating functions calculated according to (15) showed small differences between them within the range of 6-14 years of vehicle operation (e.g. in Fig. 6a).
- In several cases, the use of a 3<sup>rd</sup> degree polynomial resulted in the showing of an excessive growth in the mileage value in the 18<sup>th</sup>, 19<sup>th</sup>, and 20<sup>th</sup> year of vehicle operation (Fig. 6c).
- The use of 2<sup>nd</sup> degree polynomials eliminated the deviations mentioned above but the value of the coefficient of determination became considerably lower than that for polynomials of higher degrees.
- The use of a 4<sup>th</sup> degree polynomial resulted in a formal improvement in the model quality, manifested in a growth in the coefficient of determination; however, the approximating function showed excessively dynamic changes in the final part of the vehicle operation period (e.g. fluctuations in the function values, see Figs 6b and 6d).



Fig. 6. Results of the calculations of  $X_{Ek}$ ,  $X_{Qk}$ , and  $M_{0k}$  (points) and approximating functions  $\hat{y}$  according to (15) and (16): a and b – for vehicles of category S03; c and d – for vehicles of category S12

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Fig. 7. Curves representing the averaged approximating function  $\hat{y}_A(\tau)$  as well as positions of points  $X_{Ek}$ ,  $X_{Qk}$ ,  $M_{0k}$ , and average values  $Y_{Ak}$ ; the example pertains to vehicles of categories S02 and S10

 

 Table 4. Values of coefficients a<sub>r</sub> of the equations that model the vehicle mileage growth process for seven categories of engine cubic capacity

Vehicle category	<i>a</i> <sub>1</sub>	<i>a</i> <sub>2</sub>	<i>a</i> <sub>3</sub>
S01	27 924	-948.56	11.623
S02	33 147	-1484.20	25.437
S03	38 692	-1554.90	22.677
S04	49 684	-2589.40	47.680
S2	53 590	314.20	-46.636
S10	109 769	-3022.80	13.339
S12	123 752	-3891.50	42.025

These findings give reasons for a need of going through the next stage of the procedure presented, i.e. the averaging of the approximating functions calculated as described above.

#### 5. Estimation of the mileage growth models

An example of using the approximating functions (15) and (16) to determine their average values  $Y_{Ak}$  and to define an averaged approximating function has been presented in Fig. 7. In the graphs, the average mileage values directly calculated from the initial data (points  $X_{Ek}, X_{Qk}$ , and  $M_{0k}$ ) have been compared with the final result shown in the form of a mileage growth model  $\hat{y}_A(\tau)$  or two vehicle categories S02 and S10. It can be seen in Fig. 7 that the curves obtained from the mileage growth model are situated close to the points that represent the average values directly calculated from the experimental data.

Fig. 8 shows a comparison between the curves representing the averaged approximating functions (17) determined at stage A6 of this



Fig. 8. Models of the process of vehicle mileage growth with vehicle operation time

procedure. The mileage growth models have been based here on polynomials:

$$L = a_3 \tau^3 + a_2 \tau^2 + a_1 \tau \tag{23}$$

where: L – vehicle mileage [km] and  $\tau$  – vehicle operation time [years].

The values of coefficients  $a_r(a_1, a_2, a_3)$  of equation (23) have been given in Table 4.

### 6. Evaluation of the conformity of models with empirical (initial) data

The mileage growth process described by the estimation of the averaged approximating function (17) was evaluated in several steps. Within this evaluation, the mileage values calculated from the models were compared with average values  $X_E$ ,  $X_Q$ , and median  $M_0$ , directly based on experimental data. Thus, the evaluation of the accuracy of the estimators determined for the mileage growth models was based on indicators of conformity of model values with empirical data. Results of the calculation of values of the indicators of conformity have been given in Table 5.

The values of standard errors of estimation  $S_E$ ,  $S_Q$ , and  $S_M$  are the basic measure of the scatter in mileage values around the values determined from the model equations; the  $V_E$ ,  $V_Q$ , and  $V_M$  values define this scatter in percentage terms. The scatter in values  $X_E$ ,  $X_Q$ , and  $M_0$  around the mileage values determined from the model does not exceed 12 %. The values of the coefficient of determination  $R^2$  of regression equations (23) for the coefficients specified in Table 4 are 0.99, i.e. these equations represent 99 % of the information contained in the sets of values  $Y_{Ak}$  (cf. Fig. 7). Figures of special importance for

	Calculations based on data from series $X_E$					
Vehicle category	$S_E$ [km]	$\overline{X}_E$ [km]	V <sub>E</sub> [%]	$R_E^2$ .	$\varphi_E^2$	
S01	14 900	10 400	7.87	0.99	0.023	
S02	12 800	9 940	6.49	0.98	0.022	
S03	11 620	9 370	4.82	0.97	0.012	
S04	28 690	22 040	10.91	0.88	0.055	
S2	41 640	31 660	7.94	0.94	0.017	
S10	87 100	66 080	11.26	0.87	0.046	
S12	76 410	61 440	8.86	0.87	0.026	
	Ca	lculations based on da	ta from series $X_Q$		-	
Vehicle category	$S_Q$ [km]	$\overline{X}_Q$ [km]	V <sub>Q</sub> [%]	$R_Q^2$ .	$\varphi_Q^2$	
S01	15 860	11 070	8.38	0.98	0.026	
S02	12 940	10 280	6.55	0.97	0.022	
S03	10 320	8 200	4.28	0.95	0.009	
S04	27 700	22 350	10.54	0.86	0.050	
S2	42 850	30 460	8.17	0.91	0.017	
S10	84 690	63 100	10.95	0.88	0.044	
S12	72 730	57 570	8.43	0.89	0.024	
	Cal	culations based on da	ta from series $M_0$			
Vehicle category	<i>S<sub>M</sub></i> [km]	$\overline{X}_M$ [km]	<i>V<sub>M</sub></i> [%]	$R_M^2$ .	$arphi_M^2$	
S01	16 630	11 050	8.78	0.97	0.028	
S02	13 800	11 300	6.99	0.94	0.025	
S03	10 130	7 800	4.20	0.91	0.008	
S04	31 400	27 010	11.94	0.83	0.062	
S2	49 750	33 740	9.49	0.92	0.023	
S10	74 490	55 380	9.63	0.88	0.034	
S12	71 510	55 610	8.29	0.90	0.023	

Table 5	Deculte of	the calculation o	fuglues	f the indicators o	fconformitu	of model w	alwas with a	morimontal data
Tuble J.	results of		j vuiues o	<i>y the maicators o</i>		j mouei v	uiues with ex	срептиении иши

Table 6. Values of the mileage covered for 10 years of vehicle operation, with estimation of their relative accuracy

Vehicle category	S01	S02	S03	S04	S2	S10	S12
Mileage L <sub>10</sub> [km]	196 010	208 490	254 110	285 590	520 680	808 750	890 390
$(S_E/L_{10})100$ [%]	7.60	6.14	4.57	10.04	8.00	10.77	8.58
$(S_Q/L_{10})100$ [%]	3.82	3.64	2.81	6.49	3.84	6.05	4.90
$(\bar{X}_E/L_{10})100~[\%]$	8.09	6.21	4.06	9.70	8.23	10.47	8.17
$(\bar{X}_Q/L_{10})100~[\%]$	4.07	3.77	2.46	6.58	3.69	5.77	4.59

the evaluation of mileage growth are the  $R_E^2 R_Q^2$  and  $R_M^2$  coefficient values, which indicate how much, in percentage terms (83-99 %, see Table 5), of the information contained in  $X_E, X_Q$ , and  $M_0$  of the experimental data has been taken into account in the models calculated.

The indicators calculated may also constitute a measure averaged for the vehicle operation period. Example values of this measure, expressed in percentage terms as the quotient of the values of absolute indicators (18 and 19) to mileage value  $L_{10}$ , have been given in Table 6. Thus, the average values of the indicators have been considered in relation to the value of the mileage achieved in the middle of the vehicle operation period. These calculations were carried out with using the mileage values obtained from the models having been developed.

The relative error values specified above, calculated for the middle of the target mileage, do not exceed 11 % of the mileage covered for 10 years of vehicle operation.

#### 7. Recapitulation and conclusions

A several-stage process of the estimation of coefficients of the mileage growth models prepared for motor trucks was carried out and then the accuracy of these calculations was evaluated. The values of the evaluation measures, determined in this process, characterize the
accuracy of calculations of the mileage growth during a 20-year period of vehicle operation. The calculations covered seven categories of engine cubic capacity and two vehicle groups, with GVM of up to and above 3.5 tons (metric). The mileage growth process was evaluated on the grounds of the values of five different indicators defined by equations (18)-(22), based on a comparison of mileage values directly calculated from experimental data with values obtained from the models. Both absolute indicators (standard error of estimation, mean absolute error) and relative indicators (coefficients of determination, coefficient of variation in the error of estimation, and fraction of variance unexplained – FVU) were used.

The conclusions that can be drawn from the evaluation of the process of growth in the motor truck mileage may be formulated as follows:

- Due to the wide scatter in mileage values (coefficient of variation W > 0.5), which resulted from diversity of transport jobs, a specially prepared estimation procedure had to be used in order to obtain adequate reliability of the description of the mileage growth process.
- The outliers-removal procedures applied had a favourable impact on concentration of the mileage values around the mean level and, at the same time, did not considerably affect the said mean value (see Table 3).

- The values of the coefficients of determination  $R_{E,Q,M}^2$  show that a very big part of the initial information (0.83-0.99, see Table 5) contained in the experimental data ( $X_E, X_Q$ , and  $M_0$ ) was retained in the mileage growth models having been created.
- The high quality of the procedure adopted to evaluate the mileage growth process was confirmed by the coefficients of variation in the error of estimation  $V_E$ ,  $V_Q$ , and  $V_M$ ; as a relative measure of the scatter in the mileage values, they did not exceed 12 % of the average values of the experimental data.

The calculations carried out made it possible to obtain original values of the coefficients of equations of the models representing the current processes of growth in the motor truck mileage values in Poland. The calculations covered practically all the categories of the motor vehicles used for road cargo transport. The values of the indicators of evaluation of the mileage growth models having been developed within this work confirmed high quality of the calculations carried out, the results of which will find application in many areas, e.g. planning, forecasting, and managing of the motor truck operation or life cycle assessment (LCA) of motor trucks in terms of exhaust emissions and energy consumption.

### References

- 1. Chłopek Z, Bebkiewicz K. Model of the structure of motor vehicles for the criterion of the technical level on account of pollutant emission. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2017; 19(4): 501-507, https://doi.org/10.17531/ein.2017.4.2.
- Clarke D D, Ward P, Bartle C, Truman W. An in-depth study of work-related road traffic accidents. Road Safety Research Report No. 58. London: Department for Transport, 2005.
- Droździel P, Krzywonos L. A model of the economic effectiveness of the truck transportation services. Transport Problems 2010; 5(4): 49-56.
- 4. External costs of transport Update study. Final Report. Zurich/Karlsruhe: INFRAS, 2004.
- 5. Highway Statistics 2008. Washington: Department of Transport, 2008.
- Hultkrantz L, Nilsson J-E, Arvidsson S. Voluntary internalization of speeding externalities with vehicle insurance. Transportation Research Part A 2012; 46: 926-937, https://doi.org/10.1016/j.tra.2012.02.011.
- 7. Info-Ekspert Computer system. Catalogs. www.info-ekspert.pl.
- Krysicki W, Bartos J, Dyczka W, Królikowska K, Wasilewski M. Rachunek prawdopodobieństwa i statystyka matematyczna w zadaniach (Probability theory and mathematical statistics in problems). Part I. Rachunek prawdopodobieństwa (Probability Theory); Part II. Statystyka matematyczna (Mathematical statistics). Warszawa: PWN, 2002.
- 9. Lapparent M (de), Cernicchiaro G. How long to own and how much to use a car? A dynamic discrete choice model to explain holding duration and driven mileage. Economic Modelling 2012; 29: 1737-1744, https://doi.org/10.1016/j.econmod.2012.05.018.
- Macián V, Tormos B, Riechi J. Time replacement optimization model: comparative analysis of urban transport fleets using Monte Carlo simulation. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2017; 19(2): 151-156, https://doi.org/10.17531/ein.2017.2.1.
- 11. Mendyk E. Ekonomika transportu (Economics of transport). Poznań: Publishing House of the Poznan School of Logistics, 2009.
- Meurs H, Haaijer R, Geurs K T. Modeling the effects of environmentally differentiated distance-based car-use charges in the Netherlands. Transportation Research Part D 2013; 22: 1-9, https://doi.org/10.1016/j.trd.2013.02.013.
- 13. National Travel Survey. Statistical Release. Department of Transport. UK 2013. national.travelsurvey@dft.gsi.gov.uk.
- Opoczyński K. Synteza wyników GPR 2015 na zamiejskiej sieci dróg krajowych (Synthesis of results of the General Measurement of Road Traffic on the extra-urban network of national roads in 2015). Warszawa: Transprojekt-Warszawa, 2016.
- 15. Paefgen J, Staake T, Fleisch E. Multivariate exposure modeling of accident risk: Insights from Pay-as-you-drive insurance data. Transportation Research Part A 2014; 61: 27-40, https://doi.org/10.1016/j.tra.2013.11.010.
- 16. Piernikarski D. Reduction of fuel consumption in commercial vehicles as a factor influencing transport efficiency. Combustion Engines 2013; 154(3): 663-669.
- 17. Poulter D R, Chapman P, Bibby P A, Clarke D D, Crundall D. An application of the theory of planned behaviour to truck driving behaviour and compliance with regulations. Accident Analysis and Prevention 2008; 40: 2058-2064, https://doi.org/10.1016/j.aap.2008.09.002.
- Prochowski L. Analysis of the Relations between the Road Category and the Fatality of Road Transport Accidents. Logistics and Transport 2012: 14(1): 5-16.
- 19. Prochowski L. Characteristic features of the relation between motor truck mileage and engine cubic capacity. Journal of KONES Powertrain and Transport 2016; 23(4): 403-412, https://doi.org/10.5604/12314005.1217257.
- 20. Puentes R, Tomer A. The Road Less Travelled: An Analysis of Vehicle Miles Travelled Trends in the U.S. Metropolitan Infrastructure Initiative Series. Washington: Brooking Institution, 2009.
- 21. Redmer A, Kiciński M, Rybak R. Freight Fleet Management the methods. Gospodarka materiałowa i logistyka 2014; 4: 11-18.
- 22. Automotive Industry Reports. Year Books 2008, 2012, 2014, 2016. Warszawa: Polish Automotive Industry Association, 2008-2016.

- 23. Small K A. Energy policies for passenger motor vehicles. Transportation Research Part A, 2012; 46: 874-889, https://doi.org/10.1016/j. tra.2012.02.017.
- 24. Transport Activity Results in 2014. Warszawa: Central Statistical Office, 2015.
- 25. Transport Statistics Great Britain, The Stationery Office. London: Department for Transport, 2006.
- 26. Vehicle Survivability and Travel Mileage Schedules. Report NHTSA's. Washington: National Center for Statistics and Analysis, 2006.
- 27. Vierth I, Schleussner H. Impacts of different environmentally differentiated truck charges on mileage, fleet composition and emissions in Germany and Sweden. Stockholm: CTS Working Paper, 2012.
- 28. Zeliaś A, Pawełek B, Wanat S. Prognozowanie ekonomiczne. Teoria, przykłady, zadania (Economic forecasting. Theory, examples, problems). Warszawa: PWN, 2003.

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# Aleksander WALISZYN Andrzej ADAMKIEWICZ

# A METHOD OF VIBRATION DAMPING FOR DIESEL ENGINE CYLINDER LINERS TO PREVENT THE CONSEQUENCES OF EROSION

# METODA TŁUMIENIA DRGAŃ TULEI CYLINDROWYCH SILNIKÓW O ZAPŁONIE SAMOCZYNNYM ZAPOBIEGAJĄCA KONSEKWENCJOM EROZJI\*

This article presents the utilitarian need to determine the free vibrations of marine Diesel engine cylinder liners and the authors' own studies in this area. Theoretical investigations on free vibrations and experimental ones on forced vibrations have been described. Theoretical studies have been conducted with the application of characteristic dimensionless numbers in the Elektroniks Workbench and Wis Sim digital environment enabling virtual modeling of cylinder liner vibrations and determination of their characteristics: amplitudes, frequencies and accelerations. In the theoretical examination mechanical and electrical system analogues have been applied. A calculation method for the cylinder liner vibration damper, developed as a result of the study, has been discussed. Electrical oscillation damping filter design methods basing on the Bessel, Batterword and Chebyshev polynomials have been used. The course of the experimental examinations has been described and their results have been presented. Validation of the developed method has been executed applying measurement results concerning the parameters of Diesel engine cylinder liner vibration with various elastic elements. The results of the authors' own, theoretical and experimental, examinations have been confronted with those obtained by other scholars.

Keywords: cylinder liner, vibration damping, damper, cooled surface erosion, virtual modelling.

W artykule uzasadniono potrzebę określenia drgań własnych tulei cylindrowych silników okrętowych o zapłonie samoczynnym. Opisano badania własne w tym zakresie: teoretyczne dotyczące drgań własnych i eksperymentalne, dotyczące drgań wymuszonych.W badaniach teoretycznych do modelowania zastosowano liczby kryterialne podobieństwa z wykorzystaniem środowiska cyfrowego Elektroniks Workbench i Wis Sim. Umożliwiły one modelowanie wirtualne drgań tulei cylindrowych i określenie ich charakterystyk: amplitudy, częstości i przyśpieszenia. W badanach tych zastosowano analogi układów mechanicznych i elektrycznych. Opracowano metodę tłumienia drgań tulei cylindrowych z zastosowaniem filtrów tłumienia drgań elektrycznych w oparciu o wielomiany Bessela, Batterworda i Czebyszewa. Opisano przebieg badań eksperymentalnych i pokazano otrzymane wyniki. Walidację opracowanej metody przeprowadzono wykorzystując wyniki pomiarów parametrów drgań tulei cylindrowej silnika spalinowego z różnymi elementami sprężystymi. Skonfrontowano wyniki badań własnych z wynikami badań innych badaczy.

*Słowa kluczowe*: tuleja cylindrowa, tłumienie drgań, tłumik, erozja powierzchni chłodzonej, modelowanie wirtualne.

# 1. Introduction

Cylinder line vibrations bring about the occurrence of cavitation in cooling systems of ship Diesel engines [1, 10] especially in the medium- and high-speed ones. Therefore, damping cylinder liner vibrations is an important issue already at the designing and engine construction stage and at the same time it is an important way to maintain durability of such engines especially the trunk piston ones. In those engines, the passage of the connecting-rod through the upper and lower dead centres in the cylinder generates vibrations of high frequency. They cause erosive damage - surface degradation of the cooled part of the liner due to cavitation in the cooling liquid [3, 4, 5, 7, 16]. Erosive degradation of the surface significantly lowers durability of the cylinder [9] liner and at the same time the hourly service life of the whole engine. An effective method of preventing erosion of the surface of chilled internal combustion engines is presented in [1, 4], where for protection of metal cylinder liners and block mantle it is recommended to add chilled water containing nickel salts. The nickel layer well protects the metal from the impact of implosive gas-vapor bubbles [4]. However, it is not always possible to use this additive

in cooled water due to the difficulty of its production. In literature the solution to the problem of cylinder liner vibrations, and at the same time protection of their cooled surfaces, is realized throughout mathematical models of the studied process reflecting with the highest probability real operational conditions of cylinder liners [5, 12, 16], including the application of simulation [13] with ANSYS software[11], vibration analysis based on clusters [17] and the method of finite elements [6].

The aim of the study is to find another, less labour-consuming utilitarian method of cylinder liner vibration damping which at the same time prevents the erosion wear of the Diesel engine cylinder jacket.

In this case, the purpose of damping the surfaces of the chilled internal combustion engines is to reduce the vibration of the cylinder liners. To prevent such phenomena it is necessary to develop a model of the studied process which will with high probability correspond with real operational conditions of the liner during engine operation.

Applying theories of probability to construct engineering models enables the transfer of results obtained in a theoretical way and in laboratories to technical scale. The use of similarity criterion numbers

<sup>(\*)</sup> Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

simplifies the studies and lowers their costs. To do this, the following similarities are used [15]:

- geometric one which is fulfilled when shapes and respective geometric dimensions are proportional. As a criterion of similarity one takes the ratio of two characteristic linear dimensions (e.g. diameters),
- kinematic one (of physical fields) having geometric similarity (e.g. distribution of pressure or velocity lines), with the maintained similarity of physical fields (distribution of lines of those fields). As a coefficient of similarity one takes the ratio of two characteristic values,
- dynamic one which is fulfilled when coefficients of similarity of different characteristic values significant for a given phenomenon e.g forces of inertia or viscosity remain in strictly determined relationships (criterion numbers e.g. Froud number, Reynolds number for flows).

### 2. Determination of cylinder liner natural vibrations throughout the virtual modelling method

Determination of geometric or kinematic similarity coefficient is not usually problematic. The situation is more complex in the case of dynamic similarity. While solving the problem the possibility to represent a cylinder liner as a string of linked cylinder rings of a simple shape was used. An example of cylinder liner decomposition for a Diesel engine of the 4Cz8,5/11 type is shown in Fig 1 [15].





Such treatment of a cylinder liner enabled the application of the electromechanical analogue method to construct its virtual model [2]. The electromechanical analogue method was created on the basis of similarity of differential equations of electrical and mechanical systems. That method was used by Faraday and Maxwell, who using mechanical models tried to present in a more understandable way the hardly identified at that time electromagnetic processes.

Analogy of similarity between mechanical and electric phenomena was illustrated using mechanical and electrical systems corresponding to the following equations: it:

$$L\frac{\mathrm{d}^2 q}{\mathrm{d}t^2} + R\frac{\mathrm{d}q}{\mathrm{d}t} + \frac{q}{c} = e \tag{1}$$

- for the oscillatory electrical circuit:

n

$$C\frac{\mathrm{d}e}{\mathrm{d}t} + \frac{e}{R} + \frac{1}{L}\int e\,\mathrm{d}t = i \tag{2}$$

- for a mechanical oscillating system of a mass suspended on a string:

$$m\frac{\mathrm{d}v}{\mathrm{d}t} + b\frac{\mathrm{d}x}{\mathrm{d}t} + kx = f \tag{3}$$

or

$$u\frac{\mathrm{d}v}{\mathrm{d}t} + bv + \frac{1}{k}\int v\,\mathrm{d}t = f \tag{4}$$

From the mathematical point of view equations (1)-(4) are similar. From the identity of equations of the mechanical system and the similarity of the electrical one results that the inductance L corresponds to mass m; electrical charge q to displacement x; electrical resistance Rto dissipation coefficient b; electrical capacity C to rigidity k; voltage e to force f. It is the first form of the analogy. The second one suggested later by Chienla and Fajierstonoma, is based on the identity of equations for a mechanical system and a similar electrical circuit [13, 14]. It results from them that electrical capacity C is an analogue of mass m; voltage e of velocity v; conductivity 1/R of dissipation coefficient b; inductance L of elasticity k; electrical current I of force f.

Table 1 shows basic values and their corresponding analogues[14].

Table 1. Values and their corresponding analogues for the force-voltage and force- electrical current similarities

String	Ana- logues	Values-analogues					
Mechanical		Force (F)	Velocity ( <i>V</i> )	Mass (m)	Dissipation coefficient (b)	Rigidity ( <i>k</i> )	
	Force– voltage	Voltage ( <i>U)</i>	Current (1)	Inductance (L)	Resistance (R)	1/C	
Electrical	Force– current	Current (1)	Voltage ( <i>U</i> )	Electrical capacity ( <i>C</i> )	Conductiv- ity 1/R	1/L	



Fig. 2. A diagram of a mechanical representation of a cylinder liner of a 4Cz8,5/11 type engine in the form of a two-terminal network

Replacing real elements with their respective ones in the form of two-terminal networks characterising mass, energy dissipation and rigidity, a string of decomposed elements of the studied cylinder liner was constructed. An example of a mechanical network of a cylinder liner of the 4Cz8,5/11 type engine is shown in Fig 2.

Symbols  $M_1$ ,  $M_2$ , ...,  $M_9$  denote two-terminal networks characterizing ring mass; symbols  $k_1$ ,  $k_2$ , ...,  $k_9$  denote twoterminal networks characterizing ring rigidity; symbols  $W_1$ ,  $W_2$ , ...,  $W_9$ , denote two-terminal networks characterizing dissipative properties of the rings, F – active two-terminal network of force, determined by the magnitude of piston force interaction with the liner, evoking its vibrations when the piston passes through the upper and lower dead centres. The values of rigidity, mass and dissipation of cylinder liner rings were determined on the basis of an equation developed for a certain natural ring frequency according to Timoszenko's equation [12].

$$\omega^{2} = \frac{D_{sz}}{R^{4}\rho\delta} \frac{n^{2} (n^{2} - 1)^{2}}{(n^{2} + 1)}$$

(5)

where:  $D_{sz}$  – cylindrical rigidity of the liner;

- R external liner radius;
- $\rho$  ring material density;
- $\delta$  ring crosswise area;
- n the number of radial half-waves appearing with ring deformation resulting from vibrations.

Rigidity of the ring liners was determined depending on the value of the r/l ratio where:

1 – the length of a ring liner. For the third ring, for which  $r/l \le 0, 1$  equation (5) after transformations becomes:

$$k = \frac{EJ}{r^4} \frac{n^2 \left(n^2 - 1\right)^2}{\left(n^2 + 1\right)}$$
(6)

where: E -modulus of elasticity of the ring material;

J – moment of inertia of the ring cross-section surface.

For all the remaining rings with the  $r/l \ge 0,1$  ratio elasticity was determined from equation [14]:

$$k = \frac{E\delta\left(\frac{\pi r}{l}\right)^{4} + \frac{EJ}{r^{2}}\left(n^{2} - 1\right)^{2}n^{4}}{r^{2}\left(\left(\frac{\pi r}{l}\right)^{2} + \left(n^{2} + 1\right)n^{2}\right)}$$
(7)

whereas ring mass was found from:

$$m_i = \rho_i \,\delta_i L_i \tag{8}$$

Dissipation of particular rings  $b_i$  was determined using the logarithmic damping decrement:

$$b_i = \frac{1}{\pi} \theta \sqrt{m_i k_i} \tag{9}$$

Table 2. Values of mass, elasticity and dissipation of particular cylinder liner rings of a Diesel engine of the 4Cz 8,5/11 type

Ring number	$\delta_i(m)$	$m_i = \rho \delta_i  (\text{kg})$	<i>k<sub>i</sub></i> (N/m)	$b_i = \frac{1}{\pi} \theta \sqrt{m_i k_i} $ (N·s/m)
1	2,985 10 <sup>-03</sup>	23,399	6,741 10 <sup>11</sup>	3,641 10 <sup>04</sup>
2	1,414 10 <sup>-03</sup>	11,084	3,529 10 <sup>11</sup>	$1,813 \ 10^{04}$
3	4,000 10 <sup>-03</sup>	31,36	1,462 10 <sup>09</sup>	6,013 10 <sup>03</sup>
4	1,414 10 <sup>-03</sup>	11,084	3,529 10 <sup>11</sup>	$1,813 \ 10^{04}$
5	6,872 10 <sup>-04</sup>	5,388	1,811 10 <sup>11</sup>	9,055 10 <sup>03</sup>
6	1,414 10 <sup>-03</sup>	11,084	3,529 10 <sup>11</sup>	$1,813 \ 10^{04}$
7	6,872 10 <sup>-04</sup>	5,388	1,811 10 <sup>11</sup>	9,055 10 <sup>03</sup>
8	1,414 10 <sup>-03</sup>	11,084	3,529 10 <sup>11</sup>	$1,813 \ 10^{04}$
9	1,118 10 <sup>-03</sup>	8,768	2,852 1011	1,450 10 <sup>04</sup>
10	8,388 10 <sup>-04</sup>	6,576	2,137 10 <sup>11</sup>	$1,087 \ 10^{04}$

Assuming that the liner is made of steel of 7480 kg/m<sup>3</sup> density, mass, rigidity and dissipation of particular rings were calculated for the studied Diesel engine of the 4Cz8,5/11 type from equations (6)-(9) and listed in Table 2.

The second stage of cylinder liner model development was to change the mechanical two-terminal network into electrical network in Elektronics Workbench (EWB) virtual environment. That approach was based on physical analogies between mechanical and electrical vibrations described by differential equations (1)-(4).

Resistors, condensers without charging losses and inductance without resistance are the basic electrical two-terminal networks. Mathematical model of a resistor is an algebraic equation (Ohm's Law)  $\Delta U = IR$ , where:  $\Delta U$  - voltage drop at the resistor in V; I – current intensity in A; R – resistance of a resistor in  $\Omega$ . Models of a condenser and inductance are ordinary differential equations of the first order :  $I = C(d\Delta U/dt)$ ;  $\Delta U = L(dI/dt)$ , where: C – condenser capacity in Farads; L – conductivity in Henries. Besides passive elements of the electrical circuit there are also active elements to which belong the sources of voltage and current. For the mechanical system, an analogue to Ohm's Law is::  $F = R_m \gamma$ , where;  $\gamma$  – internal friction coefficient,  $R_m$  – analogue of electrical resistance. A change of force in time leads to a change of displacement. After differentiating the equation x = F/c versus time the following was obtained:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = V = k_m \frac{\mathrm{d}F}{\mathrm{d}t} \tag{10}$$

where: V – velocity of displacement of the point of application of force;

$$k_m$$
 – rigidity.

Spring susceptibility was considered as an analogue of electrical condenser capacity because in elastic systems the relationship between the velocity of displacement and the velocity of force change is analogical to  $I = C \frac{d\Delta U}{dt}$  for an electrical condenser. In accordance with the second Newton's Law:

$$F = m\frac{\mathrm{d}V}{\mathrm{d}t} = L\frac{\mathrm{d}V}{\mathrm{d}t} \tag{11}$$

body mass is an equivalent of electrical inductivity in modeling the anologue *Force –Voltage*. In accordance with the induced analogues,

Table 3. Calculated values of properties of elements of an electrical network

Ring number	Inductivity L (mHn)	Electrical capacity C (nF)	Resistance <i>R</i> (Ω)
1	1,484	23,399	2,308
2	2,833	11,084	4,635
3	72,87	31,36	13,97
4	2,833	11,084	4,635
5	5,522	5,388	9,281
6	2,833	11,084	4,635
7	5,522	5,388	9,281
8	2,833	11,084	4,635
9	3,506	8,768	5,797
10	4,679	6,576	7,733

between the mechanical and electrical values for the sake of determining parameters of an electrical circuit the following correlations were established: mass element m<sub>i</sub>, in kg corresponds to electrical capacity C<sub>i</sub> in nano-Farads; elasticity elements k<sub>i</sub>, in N/m correspond to inductivity in Henries, as  $1/L = k_{i,}$  and dissipation of elements b<sub>i</sub>, in Ns/m to electrical resistance R<sub>i</sub>, defined as R=1/b<sub>i</sub> in Ohms. The calculated parameters of equivalent elements of an electrical circuit for a cylinder liner of a 4Cz8,5/11 type engine are shown in Table 3.

On the basis of the values of elements of an electrical network listed in Table 3 values of elements (resistors, condensers and induction coils) necessary to construct a network were determined. Representation of a cylinder liner of the 4Cz8,5/11 type engine in an electrical form is shown in Figure 3 [13].



# *Fig. 3. A diagram representing a cylinder liner of a 4Cz 8,5/11 type engine in the form of an electric network*

Using the representation of the cylinder liner in the form of an electrical network to determine the frequency of the first harmonic vibration of the cylinder liner, a virtual experiment has been carried out

Table 4. Vibration frequencies of a cylinder liner of the 4Cz8,5/11 type Diesel engine

natural vibrations in the	liner natural vibrations	the 4Cz8,5/11 engine in an experiment
virtual experiment	on a technical scale [15]	on a technical scale [7]
1720,5 Hz	1727±198 Hz	1874 Hz

which used a generator inducing sinusoid, triangular and rectangular signals of a known frequency, amplitude and displacement. To monitor the experimental results, a two-channel oscillograph was used in the network. A piston stroke in the cylinder liner in the experiment was simulated by a short rectangular impulse whose duration was equal to the real piston stroke. For this reason in the physical model the duration of the stroke signal was estimated using a "Bordeaux " type oscillograph. Rectangular impulses in compliance with the frequency of piston strokes against the liner and the rotational speed of the engine shaft were set on the signal generator. The duration of stroke time was imitated by the value of the impulse-width signal modulation coefficient. In further studies, short strokes were imitated by Dirac's impulses. Experimental results of vibration frequency of the first harmonics of a cylinder liner for the 4Cz8,5/11 type Diesel engine turned out to be close to those obtained in studies carried out at an experimental stand (further described in part 3) and with the results from another study [7], which is shown in Table 4.

### 3. Modelling cylinder liner vibration damping

While considering a cylinder liner of a diesel engine as a series of subsequently connected rings (see Fig1) they were treated as a string of vibrating elements with their own transmittance. (Transmittance is the ratio of the output value versus the input values of variables at zero initial conditions.) If the vibrating element is described by a differential equation of the second order in the following form:

$$T_2^2 y'' + 2b_i T_1 y' + y = kx$$
(12)

then the transmittance of vibrating elements is described by the equation below:

$$W_p = \frac{k}{T_2^2 p^2 + 2b_i T_1 p + 1}$$
(13)

where: p – Laplace's operator,

k – amplification coefficient,

 $b_i$  dissipation of the rings.

 $T_1$ i $T_2$  transmittance coefficients were calculated solving the iterative equations (14)-(15):

$$b_i \frac{T_1}{2T_2}$$
 (14)  $\omega = \frac{\sqrt{4T_2^2}}{2T_2^2}$ , (15)

where:  $\omega = 2 \cdot \pi \cdot f$  – angular velocity;

f – known natural vibration frequency of rings (Hz).

Time constants  $T_e$  can be determined solving the equation:

$$T_2 = \frac{T_e}{\sqrt{\omega^2 \cdot T_e^2 + 1}} \tag{16}$$

In the studies a simpler method was applied using the Vis Sim library. Determining experimentally the frequency of natural vibrations

and the time constant (14), transmittance was calculated (13). The calculated values of time constants and natural vibration frequencies are listed in Table 5.

On the basis of parameters listed in Table 5, in the Vis Sim environment a functional

Table 5. Values of time constants and natural vibration frequencies of particular rings of a cylinder liner of the 4Cz8,5/11 type engine

Ring liner number	$T_e$ (s)	f(Hz)	<i>T</i> <sub>1</sub> (s)	<i>T</i> <sub>2</sub> (s)
1	14,00.10-6	24820	4,86·10 <sup>-6</sup>	5,83·10 <sup>-6</sup>
2	17,00·10 <sup>-6</sup>	23421	4,69·10 <sup>-6</sup>	6,31·10 <sup>-6</sup>
3	3100,00.10-6	1619	6,23·10 <sup>-6</sup>	98,31·10 <sup>-6</sup>
4	6,24·10 <sup>-6</sup>	46567	2,88·10 <sup>-6</sup>	2,99·10 <sup>-6</sup>
5	6,26·10 <sup>-6</sup>	45487	2,98·10 <sup>-6</sup>	3,06·10 <sup>-6</sup>
6	6,24·10 <sup>-6</sup>	46567	2,88·10 <sup>-6</sup>	2,99·10 <sup>-6</sup>
7	6,26·10 <sup>-6</sup>	45487	2,98·10 <sup>-6</sup>	3,06·10 <sup>-6</sup>
8	6,24·10 <sup>-6</sup>	46567	2,88·10 <sup>-6</sup>	2,99·10 <sup>-6</sup>
9	58,84·10 <sup>-6</sup>	12183	5,57·10 <sup>-6</sup>	12,76·10 <sup>-6</sup>
10	2,30·10 <sup>-6</sup>	77121	2,05·10 <sup>-6</sup>	1,54·10 <sup>-6</sup>



Fig. 4. A diagram of a functional model of a cylinder liner of the 4Cz8,5/11 type engine in the Vis Sim environment

model of an engine cylinder liner was constructed and shown in Figure 4. The model comprises blocks simulating piston strokes in the upper and lower dead point, a block summing up the results of the two strokes and a block reflecting the results.

In order to damp electrical signals electronic systems contain the most frequently used filters from the Vis Sim electronic environment library: Bessel's, Batterword's and Chebyshev's filters differing because of the used polynomials. The results of cylinder liner of the 4Cz8,5/11 type engine vibration damping obtained from the studies carried out on the liner model pointed to Chebyshev's filter as the



Fig. 5. Results of vibration damping effectiveness of a cylinder liner of the 4Cz8,5/11 type engine obtained using different filters

most effective one. It is confirmed by the runs of results of cylinder liner vibration damping efficiency obtained using the above mentioned filters which are shown Figure 5.

# 4. Experimental validation of study results

In engineering practice the most effective are the filters which are the result of synthesis of ready-made step structures with inductivities as lengthwise elements and capacities as crosswise structures. Figure 6 shows examples of Chebyshev's filters diagrams of the third order consisting of three types of elements: resistance, electrical capacity and inductivity [15].

Performing a reverse transition to the one described at the beginning i.e. going from electrical to mechanical analogies, it was stated that the actual damper of cylinder liner mechanical vibrations constructed using Chebyshev's polynomial must possess as subsequent linked elements: rigidity and dissipation separated by mass elements -metal foil as separators [8]. Appropriateness of the studied damper construction was checked at the experimental stand whose diagram is shown in Fig. 7 together with a description [13].

Mounting the liner in the coat was done throughout pushing the cylinder liner into a ring groove in the coat. The vibrator generated dynamic impulses in the upper and lower part of the cylinder liner inducing vibrations of 50 Hz frequency. During the study washers were used as elastic elements. They are shown together

with study results in Table 6. In order to check out the effectiveness



Fig. 6. Examples of Chebyshev's filters diagrams of the third order



Fig. 7. Experimental stand for simulation studies of cylinder liner of the 4Cz 8,5/11 type engine vibration parameters 1 – cylinder head;
2 – cylinder coat; 3 – upper clamping ring; 4 – lower clamping ring; 5 – liner; 6 – upper and lower firing pin; 7 – vibrometer TV-300; 8 – bolt; 9 – support plate; 10 – TSV-01 vibration detector; 11 – screws; 12 – vibrator; 13 – base plate

No	Elastic washer type	Top frequency (Hz)	Stable frequency (Hz)	Vibration amplitude (mm)	Displacement speed (m/s)	Vibrational acceleration (m/s <sup>2</sup> )
1	Without elastic washers	20000	58	0,593	10,027	8,26
2	Uniform rubber ( $\delta$ = 4 mm)	67,5	0,323	0,04	0,64	0,57
3	Rubber set (4 $\delta$ = 1 mm)	3,9	0,338	0,028	0,625	0.52
4	Polytetrafluoroethylene $(\delta = 4 \text{ mm})$	5,5	0,325	0,027	0,424	0,36
5	Sillicon set( $2\delta = 2 \text{ mm}$ )	7,4	0,324	0,055	0,879	0,73
6	Uniform paronit ( $\delta$ = 3 mm)	3,8	0,338	0,07	1,069	0,9
7	Paronit set $(3\delta = 1 \text{ mm})$	3,9	0,337	0,028	0,41	0,35

Table 6. Results of measurements of vibration parameters of a cylinder liner of the 4Cz8,5/11 type Diesel engine with different elastic elements at the upper dead point of the liner



Fig. 8. Amplitudes of cylinder liner vibrations measured during the experiment



Fig. 9. Velocities of cylinder liner vibrations measured during the experiment



Fig. 10. Accelerations of cylinder liner vibrations measured during the experiment

of damping using a set of elastic elements separated with middle masses, an experiment was carried out comparing damper operation with uniform elastic elements made of rubber and paronit with the same as far as the thickness goes sets of rubber and paronit washers ( $\delta = 1$ mm), separated with metal foil. The total washer thickness varied from 3 to 4 mm.

Measurements of vibration frequencies of the cylinder liner were performed using the TSV-01 detector and oscillograph. Measurements of vibration parameters of the cylinder liner like amplitude, velocity and acceleration of vibrations were performed in the planes of strokes of the firing pins in the upper and lower dead centres in perpendicular directions using the TV-300 vibrometer with the TSV-01 detector. Results of measurements of vibration parameters of a cylinder liner are presented graphically as bar diagrams in Fig. 8, 9, 10.

# 5. Conclusion

The obtained theoretical and experimental results of the study showed real possibilities of increasing resistance to cavitation erosion, preventing erosive damage to cylinder liners throughout limiting their vibrations.

The results of studies on natural vibration parameters of cylinder liners of the 4Cz8,5/11 type engine in Elektronics Workbench virtual environment turned out to be similar to experimental results obtained during the study at an experimental stand on a technical scale, with simple measurements of actual liner vibrations and results from other studies close to those obtained in [7] and about ten times below those given, among others, in Table 5 in [17].

Thus, they confirmed the appropriateness of the applied method of virtual studies for determining the characteristics of cylinder liner vibrations and further studies based on analogues derived from probability criterion numbers more reliable.

During the experiment, the effectiveness of damper construction, consisting of a set of elastic elements was verified. Amplitudes of cylinder liner vibrations, speed of its displacement and acceleration when using a damper with uniform elastic elements (paronit and rubber) are 1.5 to 2.5 times bigger than those for analogical values for a damper with separated elastic elements.

Ananalysis of results of studies on different kinds of elastic washers as elements of damper construction shown in Table 6 proves that the use of any elastic material lowers vibration parameters of cylinder liners minimizing them practically to zero values. Results obtained during the experiment confirmed the appropriateness of adjusting the elastic damper set to the reverse mode to the cylinder liner resonance.

Such behaviour of a cylinder liner is accompanied by minimum cavitation wear in the cooling fluid and as a result the liner will not undergo erosive degradation.

Metal surface scan obtain increased resistance to cavitation erosion throughout making the working medium flow laminar, covering metal surfaces with protective coats and relatively in the most simple way, in the case of vibration cavitation, through outdamping the vibrations of the washed cylinder liner.

# References

- 1. Adamkiewicz A, Valishin A. Discussion and studies of the properties of a cooling water additive preventing erosive wear of cooled surfaces of ship diesel engines. Eksploatacja i Niezawodnosc Maintenance and Reliability 2014; 16 (4): 565–570.
- Alessandronia S, dell' Isolab F, Porfiric M. A revival of electric analogs for vibrating mechanical systems aimed to their efficient control by PZT actuators. International Journal of Solids and Structures 2002; 39 (20): 5295-5324, https://doi.org/10.1016/S0020-7683(02)00402-X.
- Bhansali S S, Kongre U V, Shirgire N D, Bodade P R. Analysis and study of vibrations in view of combustion gas forces for diesel engine. Journal of Mechanical and Civil Engineering 2013; 6 (3): 48-55, https://doi.org/10.9790/1684-634855.
- Deku A, Kompella S. Cavitation in Engine Cooling Fluid due to Piston-Cilinder Assembly forces. Master's Degree Thesis, Department of Mechanical Enginnering, Blekinge Institute of Technology, Karlskrona, Sweden, 2006.
- 5. Duran M, Stoffel B, Sirok B. Development of Cavitation Erosion Model. Wear 2006: 642-655.
- Guoxing Li, Fengshou Gu, Tie Wang, Tiantian Yang & Andrew Ball. Investigation into the dynamic response of cylinder liners in an IC engine based on a validated finite-element model. Systems Science & Control Engineering 2017: 56-69.
- 7. Iwanczenko N N, Skuridin A A, Nikitin M D. Cavitation damage in Diesel engines. Maszinostroenie, Leningrad 1970 (in Russian).
- 8. Patent Ru 100140. Dynamic damper of cylinder liners of thermal engines. Valishin A G, 2010 (in Russian).
- Rejowski E, Soares E, Roth I, Rudolph S. Cylinder Liner in Ductile Cast Iron for High Loaded Combustion Diesel Engines. Journal of Engineering for Gas Turbines and Power 2012; 134 (7): 72-80, https://doi.org/10.1115/1.4006071
- 10. Stek B, Sommerfeld G, Schneider V. Cavitation on Wet cylinder liners of heavy duty diesel engines. SAE Technical Paper, 2006.
- 11. Sujithkumar AT, Vadivel N. Vibration Analysis of Cylinder Liner of a Vertical Type Diesel Engine using ANSYS. International Journal for Scientific Research & Development 2016; 4 (1): 561-567.
- 12. Vibration Problems in Engineering 5th edition by Weaver Jr W, Timoshenko S P, Young D H. ISBN: 978-0-471-63228-3, 1990.
- 13. Valishin A, Adamkiewicz A. Simulation of vibrations of mashine elements on the example of vibrations of marine diesel cylinder lines. Journal of Polish CIMAC 2012; 7(1): 12.
- Vibration in technology. Course book in 6 volumes. Ed. Czełomej V N, Vol. 6. Protection from vibrations and strokes. Ed. Frołow K V. Maszynostroenie, Moskva 1981 (in Russian).
- Waliszyn A G, Rozen B S. Vibrations of cylinder liners and cavitation changes in diesel cooling systems. Monograph. BGARF, Kaliningrad, 2010. (in Russian).
- 16. Young F R. Cavitation. Mc Graw-Hill Book Compani, 1989.
- 17. Zhiwei Guo, Chengqing Yuan, Peng Liu. Study on Identification Model of Cylinder Liner-Piston Ring Using Vibration Analysis Based on Fuzzy C-means Clustering. The Open Mechanical Engineering Journal 2012; 6 (2): 126-132.

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# FEM ANALYSIS OF PRESSURE VESSEL WITH AN INVESTIGATION OF CRACK GROWTH ON CYLINDRICAL SURFACE

# ANALIZA MES ZBIORNIKA CIŚNIENIOWEGO Z BADANIEM ROZWOJU PĘKNIĘĆ NA POWŁOCE WALCOWEJ

To ensure reliability of pressure vessels during service it is necessary to (1) know properties of materials used in their design and (2) evaluate vessels' behaviour under different working conditions with satisfying accuracy. Due to various technical and/ or technological requirements, nozzles are usually welded on vessel's shell producing geometrical discontinuities that reduce the safety factor. To evaluate their influence, vessels with two different nozzles were experimentally studied and critical areas for crack initiation have been identified by 3D Digital Image Correlation (DIC) method. After that, the numerical analysis of equivalent 3D finite element model was performed and obtained results were compared with experimental values. In the most critical area, next to the one of the nozzles, crack was initiated and then growth of the damage was simulated using extended finite element method (XFEM). In this paper evaluation of stress intensity factors (SIFs) along crack path is presented, as well as the most probable direction of the crack propagation on the shell. Based on SIFs values, critical length of the crack and number of pressure cycles to the final failure were estimated.

Keywords: XFEM; pressure vessel; 3D digital image correlation; stress intensity factor; crack growth.

Aby zapewnić niezawodność zbiorników ciśnieniowych podczas pracy, konieczna jest (1) znajomość właściwości materiałów zastosowanych do ich konstrukcji oraz (2) wystarczająco dokładna ocena zachowania zbiornika w różnych warunkach pracy. Ze względu na różne wymagania techniczne i/lub technologiczne, króćce zwykle spawa się do płaszcza zbiornika, w wyniku czego powstają geometryczne nieciągłości, które zmniejszają współczynnik bezpieczeństwa. Aby ocenić ich wpływ, przeprowadzono eksperymentalne badania zbiorników z dwoma różnymi króćcami i określono obszary krytyczne dla inicjacji pęknięć wykorzystując metodę trójwymiarowej cyfrowej korelacji obrazu (DIC). Następnie przeprowadzono analizę numeryczną równoważnego modelu elementów skończonych 3D, a uzyskane wyniki porównano z wartościami eksperymentalnymi. W najbardziej krytycznym obszarze, w pobliżu jednego z króćców, inicjowano pęknięcie, a następnie symulowano rozwój uszkodzenia przy użyciu rozszerzonej metody elementów skończonych (XFEM). W artykule przedstawiono ocenę współczynników intensyfikacji naprężeń (SIF) wzdłuż ścieżki pękania oraz najbardziej prawdopodobnego kierunku propagacji pęknięć na płaszczu zbiornika. Na podstawie wartości SIF, oszacowano krytyczną długość pęknięcia i liczbę cykli ciśnieniowych do ostatecznego uszkodzenia.

*Słowa kluczowe*: rozszerzona metoda elementów skończonych (XFEM); zbiornik ciśnieniowy; cyfrowa korelacja obrazu 3D; współczynnik intensyfikacji naprężeń; rozwój pęknięć.

# 1. Introduction

During the exploitation, pressure vessels are subjected to different load types (static, dynamic, thermal, etc.), and their failures usually occur in areas of geometrical discontinuity. The most common geometrical discontinuities are nozzles positioned on the cylindrical shell of the pressure vessel. The previous researches in the field [6, 15, 16] focused on this problem: stress and strain fields on pressure vessels with one nozzle were analysed, using analytical and numerical calculations, as well as experimental methods. Nozzles are usually positioned on cylindrical shells at angle bigger or less than 90° relative to longitudinal axis of the vessel [14, 19]. Each nozzle has its constructive characteristics, as well as specific effect on cylindrical shell strength. The aim of the research was to analyse the influence of the dimensions and positions of the two nozzles on the strain distribution on the vessel cylindrical shell subjected to internal pressure, and then to use obtained distributions for initial crack position prediction and consequent damage analysis. In general, damage to pressure vessels can be thought of as occurring in two stages: crack initiation and crack propagation. However, in conducting damage analyses on pressure vessel, it is often conservative to ignore the crack initiation process, assume that the component already contains a pre-existing crack or defect, and use the analysis technique to estimate the in-service extension of the defect [3, 12].

Hypothesizing the existence of an initial crack or defect seems especially appropriate for the case of large welded structures since the welds may contain defects (lack of fusion, voids, inclusions, etc.). Hence, characterization of the crack extension property of pressure vessel in terms of fracture mechanics parameters can be quite useful. In recent years, for evaluation of fracture mechanics parameters like stress intensity factors (SIFs) finite element method (FEM) has been used.

Many papers deal with the problems related to crack initiation and damage growth on pressure vessels. But, in the most of these investigations simple geometry was used in FEM calculations; researchers usually carry out simulations on 2D models of specimens [17, 8] and very rare on 3D models of real structure [13]. Moreover, even on 3D models of pressure vessels crack growth in plane was simulated, and only one crack direction was considered. In practice, cracks can grow in different directions (depending on the loads and constraints) and very often they change plane of propagation. This is hard to numerically simulate and therefore good evaluation of residual life of damaged structure is not easy to achieve. The best estimates are made when SIFs are known for real geometry; SIFs values obtained in FEM simulations on 2D models of specimens must be modified and adjusted in order to be used for residual life evaluation of the real structure.

In this research, numerical method known as extended finite element method (XFEM) was used in order to predict the in-service propagation of crack on the cylindrical shell of the pressure vessel. XFEM has caught a lot of attention since its inception in 1999. It is an alternative method to finite element method (FEM), which allows for the introduction of some knowledge (called enrichment) of the solution into the approximation space, using so-called the partition of unity method (PUM). Discontinuities may be incorporated into the approximation of the unknown field such that the faces and edges of the mesh do not need to match the discontinuity geometry. This way, the method permits the crack propagation without the need to remesh the domain between each step of the simulation.

The cracks are represented with the help of two signed distance functions that are discretized on the same mesh as the displacement field with first-order shape functions. After each step of the propagation simulation, the SIFs are computed from the numerical solution at several points along the crack fronts. Interaction integrals are used to extract the mixed-mode SIFs with the help of auxiliary fields. After that Paris-Erdogan crack growth model, for example, can be used for evaluation of the number of cycles that will grow crack to the critical length in the case of dynamical load.

This paper presents the application of the XFEM to the simulation of the crack propagation in pressure vessel with two nozzles under inservice loading. Firstly, 3D Digital Image Correlation Method (DIC) was used for determination of maximal strain values on the cylindrical shell of pressure vessel under different working conditions. Secondly, numerical model of the vessel was developed and values of stress and strain obtained by FEM were compared to experimental values to check the reliability of numerical model. Finally, based on the obtained results, i.e. identified areas of the greatest strain values between welded nozzles, crack was initiated in one of them and propagated using XFEM. Then, for each propagation step stress intensity factors (SIFs) have been calculated.

### 2. Experimental method

For obtaining reliable picture of pressure vessel stress-strain state, several pressure vessels with two adjacent nozzles were fabricated. Experiments were performed on horizontal pressure vessels each with the following dimensions: D = 378.4mm,  $e_a = 1.5$ , L= 770 mm. Pressure vessels were made of X5CrNi1810 material (EN 10088). Two nozzles, nozzle 1 DN50  $d_1 = 60.3$  (m  $e_1 = 2.9$ ) and nozzle 2 DN32  $d_1 = 42.4$  (m  $e_1 = 2.6$ ), were placed in the middle of cylindrical shell, so that the longitudinal axis of a nozzle was perpendicular to vessel's longitudinal axis (Figure 1). Minimum distance between two adja-

cent nozzle centres was calculated according to standard EN 13445–3. Vessels were tested on the pressure testing installation, subjected to internal pressure of water at the temperature of 20°C (Figure 2).



Fig. 1. Pressure vessel geometry (dimensions in mm)



Fig. 2. Experimental setup

1 - Stereo cameras; 2 - Vessel; 3 - Nozzle 1, DN50; 4 - Nozzle 2, DN32; 5 - Metal support; 6 - Pressure gauge; 7 - Illumination; 8 - Water pump connected to the pressure vessel.

Experimental investigation of strain distribution between two nozzles was carried out using 3D optical method [11, 2] considering that this method gives very reliable results. 3D system Aramis uses two digital cameras for full field strain measurement and enables precise determination of critical area [21, 9], i.e. the highest strain values on cylindrical shell. Parameters for basic Aramis system setup were: measuring volume 100 x 75, measuring distance 800 mm, camera angle 26°, calibration object CP20 90 x 72. Before starting the measurement, specimen surface had to be prepared and free of grease and oil. At the clean measuring surface, white paint was applied by spraying as the base colour. After the base-colour dried, stochastic pattern of black dots was sprayed. Before using the system, it was necessary to adjust the sensor unit, adjust the angle between the lens focus and aperture. To ensure dimensional consistency of the measuring system, calibration was performed with the help of calibration panel, and the entire system was calibrated. Inner pressure was applied gradually and imaging by means of 3D system was performed manually. Pressure increase was in the accordance with procedure defined in standard EN 13445-3.

Initial calculations had shown that the vessel's material would behave within its elasticity limits if applied pressure is less than 1MPa. However, during the experiments the following pressures had been used -0.5MPa, 1MPa, and 1.5MPa in order to investigate full field strain distributions between two closely welded nozzles (elastic plus plastic strain). In this paper results for 1.5 MPa internal pressure are presented and Figure 3 shows strain field obtained in this case (maximum value 0.195%).



Fig. 3. Strain distribution between nozzles for 1.5 MPa internal pressure

# 3. Finite element analysis of pressure vessel (numerical model)

Since the experiments with pressure vessels showed what was expected - maximum strain value was always near the welded nozzle DN50 – a numerical model was created with the aim of: a) checking obtained strain values and b) determining the direction of the crack growth after initiation in the area with the maximum strain. Pressure vessel model was designed in CATIA v5 and subsequently exported to Abaqus. Finite element (FE) model of the one half of the vessel was created in Abaqus (Figure 4), and initial numerical simulations (static nonlinear finite element analysis) were performed in order to verify the model fineness [17]. Besides, Abaqus included definition of material properties (steel, Young's modulus of elasticity of 210000 MPa, Poisson's ratio of 0.3, UTS = 540 MPa, Yield strength = 230 MPa), loads (uniform pressure of 1.5 MPa) and boundary conditions (type ZSYMM, with restricted one translation and two rotations, Figure 5). The FE model used in simulation had 283605 nodes and 243487 linear hexahedral elements of type C3D8R, and was obtained by means of iteration process which consisted of comparison between the nu-



Fig. 4. Finite element mesh of vessel model

merical results obtained for current, denser mesh and values obtained in calculations with coarser mesh. In each iteration process, mesh step was being refined until difference in stress and strain values in two consecutive steps was less than 5 %. When results obtained by finite element analysis were closed enough to the experimental values, numerical model was accepted as a satisfactory.



Fig. 5. Boundary condition of the type Symmetry ( $U_z = ROT_x = ROT_y = 0$ ) was applied in selected (red) area

Figure 6 shows the maximum strain value (0.209%) obtained in FE simulation. Comparing the results obtained by experimental method and numerical simulation, difference of about 7% was calculated confirming that values obtained by FE model can be considered relevant. At the same time, Figure 6 shows that area in which the crack is most likely to occur is around nozzle DN50. This was also confirmed by other authors [20] who showed that cracks appeared mostly in the areas with greatest stress/strain concentration, as can be seen in Figure 7. All of this justified the efforts aimed at defining sufficiently good FE model for a reliable simulation of a crack propagation in pressure vessel with two nozzles.



Fig. 6. Strain distribution between nozzles

### 4. Stress intensity factors evaluation

To predict life of the component or assembly subjected to time dependent crack growth mechanisms, postulates of fracture mechanics (FM) must be used. The cracking rate can be described using FM parameters such as the stress intensity factors (SIFs). When these factors are known *the critical crack size* for failure can be computed for given fracture toughness. The fatigue crack growth rate in metals can usually be described by the empirical Paris-Erdogan relationship  $da / dN = C(K)^n$  here da / dN s the crack growth per cycle, K s the stress intensity range during the fatigue cycle  $K = K_{max} - K_{min}$  ()and C and n are material constants. Damage tolerance allows subcritical cracks to remain in a component, but when they grow an allowable flaw size must be defined, usually by dividing the critical



Fig. 7. Rupture of the test vessel

size by a safety factor. The critical crack size is computed from the applied stress and fracture toughness and evaluation of service life of the structure can then be obtained by calculating the time (number of cycles) required for crack to grow from its initial size to allowable size. This is all impossible without evaluating SIFs first. There are three types of loading that a crack can experience: Mode I loading, where the principal load is applied normal to the crack plane, Mode II loading corresponds to in-plane shear loading, and Mode III refers to out-of-plane shear. A cracked body can be loaded in any one of these modes, or a combination of two or three modes. Each mode can be described by corresponding SIF. The stress intensity factor is usually given a subscript to denote the mode of loading, i.e.,  $K_I$ ,  $K_{II}$ , or  $K_{III}$  [1].

Stress intensity solutions for many configurations have been published and most of them were obtained from numerical models [5, 4, 18, 10]. A variety of numerical techniques have been applied to problems in solid mechanics, including finite difference method, boundary integral equation methods and finite element method. In recent years, the latter two have been applied exclusively, but now it seems that XFEM offers better and easier approach. XFEM is still not fully recognized and needs to prove its practical value to be generally acknowledged. SIFs obtained by using XFEM for a complex 3D geometry are still not regarded as reliable without experimental verification. Here XFEM is applied to study of the crack propagation in cylindrical shell of pressure vessel with nozzles (like that shown in Figure 7) with the purpose of demonstrating its power and contributing to more objective judgment about method usefulness.

Similarly to strain verification method explained in section 3 of this paper, results obtained by XFEM and presented here were verified using experimental data, as described in [23]. In brief, The XFEM was first used to the 3-point bending specimen (Figure 8a) to compare numerical values with the experimental results. After successful verification, the XFEM was used to simulate crack growth in casing pipe (Figure 8b), made of API J55 steel by high-frequency welding.



Fig. 8 XFEM verification: (a) standard specimen, (b) casing pipe

Residual life obtained in simulation was close to that observed in experiment with pipe.

In pressure vessel study, initial crack – defined as a semi-circle surface of radius 2 mm (which is crack size visible by eye) – emanates from the strain concentration location at the fillet between bigger nozzle and the body of the vessel. Abaqus includes defined hexahedron finite element mesh and, as Figure 9 shows, denser mesh was generated in the areas in which crack is expected to propagate (one half of bigger nozzle and along the wall of the vessel); the idea was to increase the accuracy of calculated values of SIFs along the crack front. Abaqus defines initial crack as a separate entity with no element mesh and the first step in 3D analysis of crack propagation is crack "opening" (Figure 10) followed by calculation of pressure vessel stresses which are then used for determination of SIFs in the nodes of the crack front.

It is important to emphasize that there are considerable differences between 2D simulation of crack propagations still dominant in papers [17, 8, 22] and 3D XFEM simulation shown here; the most significant difference is this: in 2D simulations, values for stress intensity factors are calculated in one point only – at the tip of the crack propagating in plane, whereas, in 3D simulations, the values are calculated in several points/nodes along the crack front that propagates in space. This way, it is possible to determine the stress intensity factors for all three modes, while 2D analysis determine K<sub>I</sub> and K<sub>II</sub> only.

Stress intensity factors Modes I, II and III were calculated by using Morfeo/Crack add-in for Abaqus [7]. This add-in uses Abaqus solutions to calculate stress intensity factors in nodes of the crack front and generates a file with results. Then, the equivalent stress intensity factor  $K_{eq}$  which combines all three SIF modes, was calculated as well as the kink angle (crack propagation angle) which defines the direction in which crack will be propagated in a next step.

After crack opening, Morfeo/Crack for Abaqus offers two choices: forced crack propagation in a plane and free crack propagation. Both options were used and since difference in cracks' paths was neg-



Fig. 9. FEM model of pressure vessel with two nozzles and initial crack (represented by semi-circled surface)



Fig. 10. Crack "opening

ligible results with forced crack propagation in a plane (maximum displacement 0.2 mm per step) will be presented here. Simulation took about 72 hours on Intel CORE i7 CPU, 32GB RAM computer and was stopped after 200 propagation steps when crack reached critical size.

### 5. Results and discussion

As Figures 11, 12 and 13 show, the crack propagated in almost vertical plane all the time, with two propagation fronts: one along the wall of the cylindrical part of the vessel and the other along bigger nozzle. It can be clearly seen that crack "separates" finite elements, which is one of the most comprehensive XFEM features. Table 1 shows values calculated by Morfeo/Crack for Abaqus after each step of crack propagation: curvilinear coordinate of each point along the crack front, coordinates of the crack front points in global *xyz* system, stress intensity factors for Modes I, II and III, as well as the values of  $K_{eq}$ . The number of output values for each propagation step might be a large and depends on the number of the finite element mesh in propagation areas; this is why values obtained during simulation had to be processed and shown afterward (Tables 2 and 3).

Based on the selected results shown in Table 2 (crack front on the cylindrical part of the vessel) and Table 3 (crack front on the nozzle),



Fig. 11. Crack position after 75 steps of propagation



Fig. 12. Stress distribution around crack tips after 75 steps of crack propagation



Fig. 13. Crack position after 200 steps of propagation

Curvilinear abscissa along the crack front	x co-ordinates of nodes on the crack front	y co-ordinates of nodes on the crack front	z co-ordinates of nodes on the crack front	Value of equivalent SIF	Value of SIF Mode I	Value of SIF Mode II	Value of SIF Mode III
0	-277,347	-18,5474	-188,277	2478,68	2490,78	-479,053	42,6997
0,126269	-277,331	-18,5242	-188,154	2480,94	2487,04	-484,733	49,5195
0,263287	-277,313	-18,4984	-188,021	2490,66	2463,7	-517,006	88,8699
0,38964	-277,298	-18,4741	-187,898	2493,88	2458,39	-524,807	92,205
0,537806	-277,29	-18,4505	-187,752	2508,74	2445,27	-547,211	63,9515

Table 1. Values calculated by Morfeo/Crack for Abaqus for each step of crack propagation

Table 2. Processed SIF values for crack front 1 on the cylindrical part of the vessel

			Value of equivalent SIF K <sub>eq</sub> (MPa mm <sup>0,5</sup> )			Value of SIF Mode I K <sub>I</sub> (MPa mm <sup>0,5</sup> )	
Step number	Number of nodes on the crack front	Max value along the front	Min value along the front	Mean value along the front	Max value along the front	Min value along the front	Mean value along the front
1	13	2401,2	1784,98	2103,819	2388,24	1765,87	2084,378
20	12	2530,55	2478,68	2509,5625	2490,78	2381,17	2426,431
40	12	2976,63	2879,66	2926,628	2889,64	2749,51	2813,652
60	12	3329,81	3258,03	3304,745	3245,59	3200,47	3219,269
80	12	3794,1	3730,47	3759,513	3939,01	3207,47	3568,737
100	12	4155,15	4105,72	4125,409	4063,45	3614,19	3816,965
120	12	4610,06	4462,29	4543,461	4310,38	4297,89	4305,255
140	12	5085,13	4908,67	5013,246	4775,6	4730,32	4749,217
160	12	5415,34	5096,83	5243,273	4998,16	4923,37	4957,057
180	16	5517,92	5315,22	5414,396	5338,76	5127,68	5263,866
200	12	6296,85	5888,71	6052,55	5300,62	5152,76	5242,615

Table 3. Processed SIF values for crack front 2 on the nozzle

			Value of equivalent SIF K <sub>eq</sub> (MPa mm <sup>0,5</sup> )			Value of SIF Mode I K <sub>I</sub> (MPa mm <sup>0,5</sup> )	
Step number	Number of nodes on the crack front	Max value along the front	Min value along the front	Mean value along the front	Max value along the front	Min value along the front	Mean value along the front
1	30	1932,43	1081,33	1480,031	1935,65	1052,13	1494,534
20	26	1893,33	1626,69	1827,87	2079,84	1194,77	1683,123
40	26	2289,28	1936,7	2131,59	2091,99	1935,72	1992,474
60	26	2527,3	2198,17	2342,659	2341,45	1858,32	2192,046
80	26	3115,72	2452,95	2707,23	3088,61	2559,95	2714,7334
100	24	3106,68	2697,76	2873,532	2864,7	2524,3	2712,103
120	24	3486,84	2893,82	3126,628	3333,48	2240,68	2867,595
140	22	3845,54	3171,49	3422,249	3654,4	3074,88	3383,961
160	22	3701,08	3601,59	3634,21	3810,09	3443,49	3597,201
180	22	4000,08	3653,25	3812,76	3731,78	3421,41	3554,598
200	22	4120	3768,69	3950,429	3960,29	3741,05	3854,280

it can be concluded that, during 200 propagation steps, number of points at which SIFs were calculated on both fronts varied a little – from 12 to 16 (front 1) and from 22 to 30 (front 2) – which implies that the fronts were formed in the areas with approximately constant mesh density. The number of nodes is larger on front 2 because the wall of the nozzle is thicker than the wall of the vessel body. Tables 2 and 3 also show minimum, maximum and mean values of  $K_{eq}$  along the fronts in selected steps, as well as minimum, maximum and mean values of  $K_I$  that show that mode I loading was the most dominant.

It should be noted that  $K_{eq}$  values noticeably varied along the crack front during many propagation steps which was expectable considering complex geometry of pressure vessel and 3D crack. For example, in step 30 which is chosen as the most illustrative, maximum  $K_{eq}$  value for front 1 was 2804.57 MPamm<sup>0,5</sup> whereas minimum value was 2661.2 MPamm<sup>0,5</sup> (Figure 14), while for front 2  $K_{eq max}$  was 2032.42 MPamm<sup>0,5</sup> and  $K_{eq min}$  was 1882.05 MPamm<sup>0,5</sup> (Figure 15), showing the differences of more than 8% along the front. Therefore, it was decided that for each step mean  $K_{eq}$  would be used as a representative value. Mean  $K_I$  values were then calculated in an analogous way.



Fig. 14. SIF values in nodes along crack front 1 (propagation step N° 30)



Fig. 15. SIF values in nodes along crack front 2 (propagation step N° 30)

### 6. Conclusions

At present, the safety performance of pressure vessels is arousing increasing attention. Many researches have been focusing on the plastic deformation of pressure vessels, but the macroscopic damage processes – including crack initiation and propagation – on these engineering structures haven't been studied yet. This paper brings one of the first attempts of real structure SIFs values estimation in the case when crack simultaneously grows in two perpendicular directions along pressure vessel cylindrical shell and nozzle. Loads measured in experiment and equivalent boundary conditions were used and crack growth obtained in simulation was analogous to cracks' expansions previously observed in vessels' exploitation. This led to conclusion that adequate SIFs values were obtained in calculations since crack growth directions and crack growth rate strictly depend on them. Based on calculated SIFs values, good predictions of residual life of damaged pressure vessel can be obtained.

The behaviour of cracked pressure vessel is explored using the XFEM, and based on the results of simulations and experiments a few conclusions can be drawn:- The initial crack was generated in the area with greatest strain concentration that was obtained during the experiment and subsequently confirmed by numerical analysis; since, in practice, damages occur in the same area (Figure 7), it can be claimed with a great deal of certainty that this is a critical area for a crack to appear on pressure vessels during their usage.

- In the beginning, the crack was positioned in such a way that it reached both cylindrical shell of the pressure vessel and bigger nozzle; therefore, during propagation, it formed two fronts propagating simultaneously with mutual angle of 90<sup>0</sup> (which again corresponds to practical situations). Because of different wall thicknesses of the cylindrical shell and bigger nozzle, these two fronts cannot extend uniformly, which was also shown by 3D simulation performed with the help of XFEM: Figure 13 clearly shows that the crack part on bigger nozzle is considerably shorter than crack part on the cylindrical shell of the pressure vessel. SIF values given in Tables 2 and 3 show that SIFs are considerably bigger for crack front 1 than for crack front 2, which is main reason why the crack propagated more on the cylindrical shell.

- Figure 16 shows an interesting observation: mean values of  $K_{eq}$  as almost linear increase during propagation of both fronts (coefficients of determination are high: 0.9959 and 0.995 respectively). This means it is possible to establish correlation between crack length, vessel wall thickness and stress intensity factor values and then evaluate crack propagation speed in a certain vessel area. An effort was made in that direction and result is shown in Figure 17. To obtain the graph of crack length vs. number of ad cycles, calculated SIF values were plugged into the Paris-Erdogan equation (with material constants n = 3.174 and  $C = 1.77195 \times 10^{-12} MPa \, mm^{1/2}$  that represent material of the vessel) and integrated. As it can be seen, through crack on cylindrical shell under 1.5 MPa pressure is growing fast: after N=1150



Fig. 16. Variations of mean  $K_{eq}$  values for both crack fronts during 200 steps of propagation



Fig. 17. Crack length on cylindrical shell as a function of number of cycles of applied load

cycles crack length is about 20 mm and after next 250 cycles its length is doubled meaning that crack reaches critical size after which complete failure occurs soon. Obtained small number of cycles indicates that vessel of this wall thickness under given pressure must be crack free because damage on the cylindrical shell grows extremely fast. However, next investigations of pressure vessel integrity must consider the influence of the type of material and wall thickness on the rate of crack growth.

- In the end, it must be kept in mind that the main advantage of XFEM lies in possibility of SIFs values evaluation on complex cracked geometry (like pressure vessel with nozzles) which then can be used for predictions of crack propagation paths and evaluations of residual life, but – at the same time – XFEM results are mesh sensitive and depend on the mesh density in the fracture process region. Mesh size must be determined carefully to ensure the computational efficiency and accuracy; therefore, experimental verification of FE model is necessary, at least in the phase when the object is still undamaged.

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# References

- 1. Anderson TL, FRACTURE MECHANICS Fundamentals and Applications, 3rd ed. CRC Press, Taylor & Francis Group; 2005.
- 2. Balac M. Nozzles interaction influence on stress state and strains on cylindrical shell of the pressure vessel. Doctoral Thesis. University of Belgrade, Mechanical Faculty; 2014.
- 4. Dębski H, Koszałka G, Ferdynus M. Application of FEM in the analysis of the structure of a trailer supporting frame with variable operation parameters. Eksploatacja i Niezawodnosc Maintenance and Reliability 2012; 14(2): 107-114.
- Falkowicz K, Ferdynus M, Dębski H. Numerical analysis of compressed plates with a cut out operating in the geometrically nonlinear range. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2015; 17 (2): 222-227, https://doi.org/10.17531/ein.2015.2.8.
- Giglio M. Fatigue analysis of different types of pressure vessel nozzle. International Journal of Pressure Vessels and Piping 2003; 80: 1–8, https://doi.org/10.1016/S0308-0161(02)00151-5.
- 7. Grbovic A, Rasuo B. Use of modern numerical methods for fatique life predictions, In: Branco R, ed. Recent Trends in Fatique Design, Nova Science Publishers, Inc. New York, 2015: 31-75.
- 8. Huffman P J et al. Fatigue crack propagation prediction of a pressure vessel mild steel based on a strain energy density model. Frattura ed Integrità Strutturale 2017; 42: 74-84.
- 9. Kawabayashi H, Matsuda H, Zhao C, Konzuma H, Yamashita T. Modeling cylindrical shell with initial imperfections by using optical method. The Fifth China Japan Joint Seminar for the Graduate Students in Civil Engineering, Shanghai, China 2008; 181-186.
- Kopecki T, Zacharzewski J. Fatique life and stress state analysis of cracked thin walled plate under cycles axial tension. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2006; 3: 19-26.
- 11. Kopecki T, Mazurek P. Determination of stress distribution patterns in post-critical deformation states of thin-walled skins subjected to operating loads. Eksploatacja i Niezawodnosc Maintenance and Reliability 2014; 16(4): 608-615.
- Liu J, Shi Z, Shao Y. An investigation of a detection method for a subsurface crack in the outer race of a cylindrical roller bearing. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2017; 19(2): 211-219, https://doi.org/10.17531/ein.2017.2.8.
- Lee K L S, Martin D. Application of XFEM to model stationary crack and crack propagation for pressure containing subsea equipment. Proceedings of the ASME 2016 Pressure Vessels and Piping Conference PVP2016 July 17-21, 2016, Vancouver, British Columbia, Canada, 1-7.
- Maghrabi S H, Mulkutkar M M, Shetty K, Aquil M. Elastic Behavior of Cylindrical Vessels with Lateral Nozzle Under Internal Pressure. International Journal of Engineering Research and Applications 2012; 2: 1029–1034.
- Ming-Hsien Lu, Jiun-Shya Yu, Jien-Jong Chen. The effect of analysis model on the stress intensity calculation for the nozzle attached to pressure vessel under internal pressure loading. International Journal of Pressure Vessels and Piping 2014; 117-118: 9-16, https://doi. org/10.1016/j.ijpvp.2013.10.004.
- Mukhtar M F, Al-Gahtani J H. Design-Focused Stress Analysis of Cylindrical Pressure Vessels Intersected by Small-Diameter Nozzles. Journal of Pressure Vessel-Transaction of ASME 2017; 139: 021205-1-11.
- Nicak T, Mutz A, Keim E, Meier G. Application of XFEM to model crack initiation and propagation during a PTS event. Proceedings of the ASME 2015 Pressure Vessels and Piping Conference PVP2015 July 19-23, 2015, Boston, Massachusetts, USA, 1-11, https://doi. org/10.1115/PVP2015-45180.
- Pathak H, Singh A, Singh VI. Fatigue crack growth simulations of 3-D problems using XFEM. International Journal of Mechanical Science 2013; 76: 112–131, https://doi.org/10.1016/j.ijmecsci.2013.09.001.
- Petrovic A, Balac M, Jovovic A, Dedic A. Oblique nozzle loaded by the torque moment stress state in the cylindrical shells on the pressure vessel. Proceedings of the Institution of Mechanical Engineers, Part C Journal of Mechanical Engineering Science 2012; 226: 567–575, https://doi.org/10.1177/0954406211415907.
- 20. Sang Z F, Xue L P, Lin, Y J, Widera G E O. Limit and burst pressures for a cylindrical shell intersection with intermediate diameter ratio. International Journal of Pressure Vessels and Piping 2002; 79: 341–349, https://doi.org/10.1016/S0308-0161(02)00028-5

- 21. Sedmak A, Milosevic M, Mitrovic N, Petrovic A, Maneski T. Digital image correlation in experimental mechanical analysis. Structural Integrity and life 2012; 12: 39–42.
- 22. Singh I V, Mishra B K, Bhattacharya S, Patil R U. The numerical simulation of fatique crack growth using extended finite element method. International Journal of Fatigue 2012; 36: 109-119, https://doi.org/10.1016/j.ijfatigue.2011.08.010.
- 23. Vulicevic L J L, Rajic A, Grbovic A, Sedmak A, Sarkocevic Z. Fatigue life prediction of casing welded pipes by using the extended finite element method. Frattura ed Integrità Strutturale 2016; 36: 46-54.

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Piotr NIKOŃCZUK

# PRELIMINARY MODELING OF OVERSPRAY PARTICLES SEDIMENTATION AT HEAT RECOVERY UNIT IN SPRAY BOOTH

# WSTĘPNY MODEL SEDYMENTACJI OSADÓW LAKIERNICZYCH W REKUPERATORZE KABINY LAKIERNICZEJ\*

Overspray sediments settling on the recuperator's fins cause operational problems. The cross sections of the recuperator's channels gradually decrease and finally it result in clogging of the recuperator. The layers of sediments cause air flow resistance and also heat transfer resistance. The paper presents preliminary results of sedimentation process modeling. The model of overspray creation takes into account a droplets size and particles concentration in air stream inside extraction ducting. Simulation results are compared with measurements conducted in three commercial spray booths.

Keywords: spray booth, sedimentation, overspray, overspray sediments.

Odkładające się na lamelach rekuperatora osady lakiernicze powodują problemy eksploatacyjne. Przekroje poprzeczne kanałów rekuperatora stopniowo zmniejszają się i ostatecznie prowadzi to do zatkania rekuperatora. Oprócz oporów przepływu powietrza osady stanowią również opór termiczny przy wymianie ciepła. W artykule przedstawiono wstępne wyniki modelowania procesu sedymentacji drobin lakieru. Zaprezentowano model powstawania mgły lakierniczej zawierającej krople lakieru o określonej średnicy oraz stopień koncentracji drobin lakieru w kanale wentylacyjnym za filtrem. Wyniki symulacji porównano z wynikami pomiarów w rzeczywistych kabinach lakierniczych.

Słowa kluczowe: kabina lakiernicza, sedymentacja, mgła lakiernicza, osady lakiernicze.

# 1. Introduction

During the operation of the spray booth in the painting mode, the air in the spray booth is constantly replaced. Worn, warm air is ejected from the work space of the cabin. In case to increase Energy



Fig. 1 A location of the heat exchanger in typical booth assembly

efficiency of spray booths the heat recovery units are used. The most popular are cross recuperators. Construction of recuperator consists of fins, which separate alternately streams of hot and cold air. Distance between fins is within range of 12 - 15 millimeters. In figure 1 is shown a diagram with the location of the cross heat exchanger in typical booth assembly.

The hot air includes overspray particles. Droplets of paint create sediments on internal parts of exhaust ducting. Sediments are also created on recuperator fins. In figure 2 is shown recuperator contaminated with overspray sediments.

Growing sediments cause resistance of heat flux and air flow [14, 15]. Finally the layer of sediments causes clogging of recuperator. It results in spray booth being inoperative because of explosion hazard.



Fig. 2 Recuperator fins contaminated with overspray sediments

(\*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

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Assessment of the risk of explosion in the spray booth is shown in [24] in relation to the powder paint shop.

The issue of the impact of deposits on the operating conditions of technical objects is present in many areas of concerns include internal combustion engines [1, 23]. In the area of spray booths, the problem of deposits was treated negligibly due to cross sections of ventilation ducts of the order of 0.8 - 1 [m]. A few-millimeter sediment layers do not have a significant impact on changing the air flow resistance in the exhaust channels. Only the appearance of recuperators in booth ventilation systems has caused the phenomenon of sedimentation of the paint overspray visible. In the technical and operational documentation of paint booths with recuperators, the need to clean up recuperators is often neglected. No limiting conditions have been defined in relation to the thickness of the deposits and the minimum cross-section of the channel in the recuperator. The limit states allow determining the exploitation time as in the case of hot water-pie [17] or engine crankshafts [21]. The volume of the used paint has a significant impact on the thickness of overspray sediments; however, it takes on variable values during the operation of the spray booth. This requires determining fixed intervals between technical inspections of the recuperator or adopting a quasi- periodic strategy [8].

There are conducted research on the atomization of varnishes [19] and the transfer efficiency of paint spray guns [18, 22]. Regulations and recommendations regarding transfer efficiency are issued by using low-pressure HVLP (High Volume Low Pressure) spray guns [26, 27]. Publications on the size of the paint mist consider it primarily in health and environmental aspects. There are also many publications on the effectiveness of paint stop filters [4, 6, 7], other media [10, 12] or alternative methods [20, 25]. However, they do not include aspects of the impact on the operational conditions of the spray booth. The problem of atomization and transfer efficiency is also an extensive issue in the field of agricultural spraying [9, 11], and [13].

Mathematical and simulation models of sedimentation of particles on the inner walls of the channels in turbulent flow are presented in [2, 3] and [5]. This article presents a preliminary mathematical and simulation model of overspray sediments growth. The developed model takes into account the adhesive properties of drops of paint. The growth rate of the sediments layer is determined on the basis of the booth working time in the painting mode and the flow rate volume of the applied lacquer.

### 2. The phenomenon of overspray aggregation

During paint application, from spray gun flows a stream of paint volume  $V_P$  in form of droplets of varied size. Droplet diameters are associated with many parameters, for example: nozzle size and spray gun settings, compressed air pressure, volume of paint stream, distance between nozzle and coated surface [19]. The largest part of paint particles deposit on painted surface and create coating. The rest of paint drops fly around painting area and create overspray. The overspray is extracted from working chamber together with exchanged air.

The volume of paint in overspray  $V_P^I$  depends on transfer efficiency *TE*:

$$V_P^I = \dot{V}_P \left(1 - TE\right) \tag{1}$$

Transfer efficiency describes volume of coated paint ratio to total volume of used paint. It is non dimensional value.

Extracted air is treated by *paint stop* filter. The filter usually is located on the floor or in the wall of spray booth. Filter efficiency  $F_E$  describes arrested particles ratio to total quantity of particles. It is percentage value. Filter efficiency is depended on particles diameter [4, 7, 6, 10, 12, 20]. Suppliers of *paint stop* filters declare filter efficiency

in given range [30] or average value [29]. Finally the volume of paint after filtration  $V_P^{II}$  can be described by equation:

$$V_P^{II} = \frac{V_P^I \left(100 - F_E\right)}{100\%} \tag{2}$$

The concentration of paint droplets degree  $p_c$  at the stream of extracted air  $\dot{V}_A$  after cleaning by paint stop filter can be calculated by equation:

$$p_c = \frac{n_p}{\dot{V}_A} \tag{3}$$

where  $n_p$  describes a stream of paint particles [1/s]. In case to find a quantity of particles  $n_p$  can be used an obvious dependence, that volume of sprayed paint is equal to total volume of all droplets of paint.

$$V_p^{II} = \sum_{i=1}^{n_p} \frac{1}{6} \Pi d_i^3 \tag{4}$$

where  $d_i$  means a diameter of *i*-particle [m]. Assuming that all paint particles have a normalized diameter  $d_A$ , the stream of paint particles can be determined from the following equation:

$$\dot{n_p} = \frac{6V_p}{\Pi d_A^3} \tag{5}$$

A normalized diameter of paint particles  $d_A$  depends on atomization conditions and distance between nozzle and coated surface. The stream of particles is expressed in units of number of particles per second [1/s].

# 3. A general model of particle deposition in turbulent flow

There are conducted researches on sedimentation of particles in turbulent flow [2, 5]. A stochastic model of particles deposition and clogging of ventilation duct was proposed in four elementary stages [3]: deposition, resuspension, agglomeration and clogging. In figure 3 are shown individual stages.

The model of particle deposition on the surface is described by energy. It is described by the energy balance in the normal direction to the wall. It consists of two basic mechanisms: the hydrodynamic transportation of particles in the turbulent flow, and the mechanism of adhesion. Adhesion is based on the physicochemical interactions between the two solids. The particles are deposited on the wall (or on already attached particles) when their energy in the normal direction to the wall is sufficient to overcome the reflection energy barrier, or otherwise bounce off the surface. The energy barrier is determined using the DLVO theory [3], named after the authors Derjaguin-Landau and Verwey-Overbeek. The theory assumes that total energy is the sum of the energy of interaction:

$$U_{part-surf} = U_{part-plate}^{DLVO} \left(1 - S_{cov}\right) + \sum U_{part-part}^{DLVO}$$
(6)



Fig. 3. Elementary stages of deposition model a) deposition, b) resuspension, c) agglomeration, d) clogging

particles. In figure 5 is shown a 3D spatial grid and particles of diameter *d*.

A steady stream of paint  $V_P = 3.33e-6$  $[m^3/s]$  (200 [ml/min]) was assumed. With such a volume of paint and the spray gun nozzle distance from the coated surface equal 0.3 [m] can be assumed normalized mean droplet of lacquer equal to  $d = 10^{-4} / m$  [19]. The flow volume of air exchanged inside paint booth had a value  $V_A = 5,56 \ [m^3/s]$  (20 000 [m<sup>3</sup>/h]). Paint transfer efficiency TE=0,65 was established on the basis of the European Union guidelines [26] recommending the use of low-pressure guns HVLP. The filter efficiency  $F_E = 94$  [%] was adopted on the basis of one of the catalogs of filter distributors [30].

where  $S_{COV}$  denotes the surface coverage of embedded particles, the  $U_{part-plate}$  means interaction between the particle and the clean surface.  $U_{part-part}$  denotes the interaction between the particles. Contact area  $S_{cont}$  specifies the contact area and is given by dependency:

$$S_{cont} = \Pi \left( 2 \sqrt{d_{part} d_{dep}} + d_{dep} \right)^2 \tag{7}$$

where  $d_{part}$  is the radius of particles and  $d_{dep}$  radius of embedded particles. If the contact zone are previously embedded particles present, is randomly selected molecule is deposited on the next random account.

Due to the phenomenon of adhesion of paint droplets, it has been recognized that in the model of sedimentation

of paints practically there is no phase of resuspension. If the particle clings to the surface, it stays there indefinitely. Two additional phenomena were proposed in the modified model: the possibility of agglomeration on the surface and the surface leveling effect. Agglomeration on the surface consists of the possibility of moving the particle by a distance equal to its diameter to another, previously settled particle. Leveling refers to the case where the drop lands on another early deposited particle to form a further layer of sediment. When in the vicinity of the drop' embedding the drop there is no particle located lower than one layer below, the particle falls to the close position in the lower layer. Agglomeration and surface leveling can take place only at the moment of deposition of particle and this can only take occur within an area of radius equal to the diameter of the drop's diameter.

# 4. Simulation model

For the proposed model a numerical model was developed. Adopted the geometry of the duct of the recuperator shown in figure 4. The recuperator is dedicated to the paint booth with an air flow volume  $\dot{V}_A = 5.56 \ [m^3/s]$  (20 000  $[m^3/h]$ ) [28]. Its construction consists of channels of width  $w_d = 1 \ [m]$ , high  $h_d = 0.012 \ [m]$  and length  $l_d = 1 \ [m]$ . Altogether there are 120 channels alternately for warm and cold air.

For simplicity, it is assumed that the diameter of a droplet of paint d has a normalized constant value. The surfaces of the recuperator fins and the space between them were separated into a three-dimensional grid consisting of cubes, having sides equal to the diameter of the



Fig. 4. Recuperator dedicated for spray booth [28]



Fig. 5. A model of 3D mesh for numerical simulations

For these parameters, the average velocity of the air flow between the fins is u = 7.7 [m/s]. For this speed the Reynolds number assumes the value Re = 10828 and indicates the turbulent flow. On the basis of generally known equations, the height of the boundary layer  $\delta_x$  for turbulent flow can be determined [16]:

$$\delta_X = \frac{0.376x}{\operatorname{Re}_x^{\frac{1}{5}}} \tag{8}$$

where x is the distance from the edge of the channel while  $\text{Re}_x$  describes the local Reynolds number at point x at the speed of the undisturbed flow of  $u_{\infty}/m/s$ ?:

$$\operatorname{Re}_{x} = \frac{u_{\infty}x}{\upsilon} \tag{9}$$

The small channels of above presented recuperator require a separate, special analysis of the boundary layer. This is due to the ratio of the length of the sides of the cross section of the single duct. According to equations (8) and (9) the thickness of the layer in half the length of the channel (x = 0.5 / m) is equal  $\delta_x = 0.0159 \ [m]$ . Considering that the channel height is  $h_d = 0.012 \ [m]$ , the height of the boundary layer cannot exceed the height of the channel. For simplicity, it was assumed that at the entire volume of exchanged air the degree of particle's concentration  $p_c$  is uniform in a turbulent flow. This also applies to the boundary layer. Similar simplification was also applied in other sedimentation models [3]. The degree of concentration of paint particles  $p_c$  describes to the amount of paint drops per 1 square meter of the air flow. In the modeled spatial grid, the thickness of the boundary layer is equal to the normalized particle diameter d. The degree of concentration of droplets  $p_c^{I}$  of paint in the boundary layer per square meter can be determined by the dependence:

$$p_c^I = p_c d \tag{10}$$

A one iteration of the process simulation was assumed as period of one second. The total number of the particles appearing in the boundary layer during given time  $\tau$  is connected with the air flow rate:

$$n_p = \int_{0}^{\tau} p_c^I F_s u_A dt \tag{11}$$

where  $u_A$  is the average velocity of the air and  $F_s$  is the surface area of the recuperator fin on which particles are deposited.

$$u_A = \frac{\dot{V}_A}{F_d} \tag{12}$$

The cross section of the ventilation duct  $F_d$  is the product of its height  $h_d$  and the width  $w_d$ . In the model, the pressure drop in the cross section of the  $F_d$  channel was neglected.

## 5. Simulation results

A number of simulations have been performed for the above parameters. The results of the calculations were considered in particular in terms of the increase in the coverage of the lamella surface in successive iterations, the number of growing layers and the mean sediment height. he present results relate to the formation of deposits on the fins constituting the two channel walls recuperator width  $w_d = 1 \ [m]$ . The side walls of height  $h_d = 0.012 \ [m]$  were neglected. In figure 6 is shown a part of the resulting matrix representing the agglomeration of overspray particles after *1e6* iterations. The coordinates in Figure 7 relate to the size of the grid shown in Figure 6. In view of the above, the agglomeration of the particles exhibits a part of lamella surface. The size of presented area is equal 4e-3 x 4e-3 [m]. The highest number of layers of sediment is equal 3, which means that maximum height of the local agglomeration has value 3e-4[m].



Fig. 6. Agglomeration of overspray particles after 1e6 iterations



Fig. 7. Coverage of fins in subsequent iterations



Fig. 8. Maximal and average number of layers in subsequent iterations

The degree of surface coverage after 1e6 iterations is relatively small. It does not reach 20% f total area. In figure 7 is shown the increase of the surface coverage of two fins of recuperator in subsequent iterations. Coverage close to 100% in both cases occurs after 12e7 iteration.

The maximum and average number of layers of sediments on the lamellas in subsequent iterations is shown in Figure 9. The maximum



Fig. 9. Distribution of the number of layers in agglomerations after selected iterations



Fig. 10. Sediments on recuperator fins after 12e7 iterations

values of the layers are not much different, while the mean values for both lamellas are the same.

In Figure 8 is shown the maximum number of layers, while in the Figure 9 is presented the change in the distribution of the layers number of sediments in the chosen iterations of agglomeration. For comparison 5e7, 10e7, and 15e7 iterations were selected.

As mentioned, the coverage of the slats reaches a value close to 100% after 12e7 iteration. Figure 10 shows the visualization of sediment concentration in the space between the two lamellas after the 12e7 iteration. The visualization shows a part of fins of the same size as in Figure 6. The average height of sediments on upper and lower fins has a value of 3e-3 [m]. This results in a half reduction of the cross section of the recuperator channel.

One iteration of the simulation relates to one second of spray booth operating in paint application mode. A comparison of numerical experiment and results of real experimental work [15] is presented in Figure 11. The values deviate significantly from each other.

The simulation results indicate a much slower rate of growth of sediments compared to the results of the real measurements. In the simulation model, the recommended values of the transfer efficiency *TE* and the maximum efficiency of the filter  $F_E$  were assumed. The efficiency of the filters can be varied [29, 30]. The results of studies conducted in the wood industry presented in work [22] show that the actual transfer efficiency with HVLP guns is within the range of TE = 20-60%. It depends on the type of material used, the spray gun quality and condition, the geometry of the surface to be covered and the skills of the painter. In Figure 12 are shown simulation results for



Fig. 11. Comparison of simulation and measurements results

different transfer efficiency values TE = 0.20 and TE = 0.55 and filter efficiencies  $F_E = 80\%$  and  $F_E = 85\%$  [29]. It is also taken into consideration that the total working time of the paint booth  $t_t$  is the sum of the coating times  $t_p$ , drying time  $t_c$  and ventilation time  $t_v$  [15]. It was assumed that the share of painting time  $t_p$  is half of the total time  $t_t$ .



Fig. 12. Results of measurements and simulations for different transfer efficiency TE and filter efficiency  $F_E$ 

The presented results concern the preliminary model of sedimentation of paint particles on the recuperator fins. Several simplifications were used. The values obtained in numerical simulations were compared with the measurement results at the three paint booths [15]. Simplification of standardized droplet diameter *d* in overspray was applied. The distribution droplet diameter depends on parameters such as the type of paint material, the spray gun nozzle size, air pressure, the volume flow of paint and the distance from the nozzle [19]. The share of paint time  $t_p$  in the total operating time of the paint booth  $t_t$  is also varied at every coating process.

### 6. Conclusion

Manufacturers and suppliers of heat recovery units for paint booths are often do not put in the technical manual requirements for inspection and cleaning of recuperators. he main objective of the model of sedimentation of spray mist particles being developed is to create a simplified dependence of the sediment growth rate on the averaged parameters of transfer efficiency *TE*, filter efficiency  $F_E$  and the share of painting time  $t_p$  in the total working time of the booth  $t_t$ . On the basis of the presented model, taking into account the above parameters, it is possible to pre-determine the working time of the spray booth, after which the recuperator should be cleaned. Assuming that the average thickness of the overspray sediment in the recuperator cannot exceed 1mm, then according to Figure 12, this takes place on average after 5e6 seconds. Therefore, the recuperator needs to be cleaned up at average intervals equal to 1389 operating hours of the spray booth. Taking into account the annual working time of 2000 hours for an eight-hour working day, this means an eight-month interval between the purifications of the recuperator. The growth rate of sediments is not uniform and takes individual values in different spray booths. These differences are presented in paper [15]. For safety reasons, considering the variance of growth rate, the time between inspections of the recuperator should not be shorter than 6 months. The presented

period of paint booth operation between the purifications of the recuperator is based on a simplified and averaged sedimentation model. These include the mean droplet size distribution of paint depending on the properties of the material used paint, the spray gun and distance from the nozzle [19]. For the individual case, the efficiency of the  $F_E$  filter used in the cabin depends on the particles size [7] statistics of the working time of the booth in painting mode, time of spray gun operation and volume of applied paint. The above sedimentation model also allows prediction of the recuperator's contamination based on the volume of the coating material  $V_p$  used inside the spray booth.

# References

- 1. Adamkiewicz A, Valishin A. Discussion and studies of the properties of a cooling water additive preventing erosive wear of cooled surfaces of ship diesel engines. Eksploatacja i Niezawodnosc Maintenance and Reliability 2014; 16 (4): 565–570.
- Agbangla G C, Climent E, Bacchin P. Numerical investigation of channel blockage by flowing microparticles. Computers & Fluids 2014; 94: 69-83, https://doi.org/10.1016/j.compfluid.2014.01.018.
- Caruyer C, Minier J P, Guingo M, Henry C. A Stochastic Model for Particle Deposition in Turbulent Flows and Clogging Effects. In: Gourbesville P, Cunge J, Caignaert G. (eds) Advances in Hydroinformatics. Springer Water. Springer, Singapore 2016: 597-6121, https://doi. org/10.1007/978-981-287-615-7\_40.
- 4. Chan T L, D'Arcy J B, Schreck R M. High-solids paint overspray aerosols in a spray painting booth: particle size analysis and scrubber efficiency. American Industrial Hygiene Association Journal 1986; 47 (7): 411-417, https://doi.org/10.1080/15298668691389964.
- Chibbaro, S., & Minier, J.-P. Langevin PDF simulation of particle deposition in a turbulent pipe flow. Journal of Aerosol Science 2008; 39 (7): 55-571. doi: 10.1016/j.jaerosci.2008.03.002. https://doi.org/10.1016/j.jaerosci.2008.03.002
- 6. Darvin C H. Fractional penetration of paint overspray arrestors. U.S. Environmental Protection Agency, Washington, D.C., EPA/600/R-97/011 (NTIS PB97-147953), 1997.
- 7. Darvin C H, Cox L S & Smith D. Comparative Study of Spray Booth Filter System Efficiency. Journal of the Air & Waste Management Association 1999; 49 (3): 339-344, https://doi.org/10.1080/10473289.1999.10463801.
- Gao W, Zhang Z, Ji H, Zhou j, Liu Q. Optimal quasi-periodic preventive maintenance policies for a repairable system with stochastic maintenance interval. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2015; 17 (3): 389–397, https://dx.doi.org/10.17531/ ein.2015.3.9.
- 9. Guler H, Zhu H, Ozkan E, Peter Ling P. Characterization of Hydraulic Nozzles for Droplet Size and Spray Coverage. Atomization and Sprays 2012, 22 (8): 627–645.
- Howarth J L, Anand S C. Design, development and characterization of a novel and innovative exhaust filter media for the global automotive industry. Textile Research Journal 2015; 86 (18): 1962-1972, https://doi.org/10.1177/0040517515619349.
- 11. Kecskésné Nagy E, Koszel M, Sztachó-Pekáry I. Effect of working parameters and nozzle wear rate onto the spray quality in use of different fan flat nozzle. Journal of Central European Agriculture 2014; 15(1): 160-174, https://doi.org/10.5513/JCEA01/15.1.1428.
- Kim H T, Jung C H, Oh S N, and Lee K W. Particle Removal Efficiency of Gravitational Wet Scrubber Considering Diffusion, Interception, and Impaction. Journal of Environmental Engineering Science 2015; 18: 125:136, https://doi.org/10.1089/10928750151132357.
- 13. Lee C, Kim D H, Koo J Y. Overspray Characteristics and Droplet Density Distribution of Low Pressure Shear Coaxial Injector. ICLASS 2012, 12th Triennial International Conference on Liquid Atomization and Spray Systems, Heidelberg, Germany, September 2-6, 2012.
- 14. Nikończuk P. Study of Heat Recovery in Spray Booths. Metal Finishing 2013; 111 (6): 37-39, https://doi.org/10.1016/S0026-0576(13)70284-8.
- 15. Nikończuk P. Preliminary analysis of heat recovery efficiency decrease in paint spray booths. Transactions of the Institute of Metal Finishing 2014; 92 (5): 235-237, https://doi.org/10.1179/0020296714Z.00000000200.
- 16. Pietrowicz S. Przejmowanie ciepła przy wymuszonym opływie wzdłuż płaskiej płyty, Laboratorium komputerowe z wybranych zagadnień mechaniki płynów, http://fluid.itcmp.pwr.wroc.pl/~znmp/dydaktyka/wzzmp/Warstwa\_przyscienna\_cw\_7.pdf (16.03.2017).
- 17. Pilch R, Szybka J, Broniec Z. Determining of hot water-pipe exploitation time on the basis of limiting states. Eksploatacja i Niezawodnosc Maintenance and Reliability 2012; 14 (3): 203-207.
- Poozesh S, Akafuah N, Saito K. Effects of automotive paint spray technology on the paint transfer efficiency a review. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2017,232 (2): 282-301 https://doi.org/10.1177/0954407017695159.
- 19. Salaimeh A, Adornato A, Akafuah N, Saito K. Assessment of Spray Envelope Using Droplet Breakup Regime and Mechanisms. ICLASS 2015, 13th Triennial International Conference on Liquid Atomization and Spray Systems, Tainan, Taiwan, August 23-2 2015.
- 20. Schweizer R. Technological Advancements in Overspray Collectors. Metal Finishing 2010; 108 (4): 38-45, https://doi.org/10.1016/S0026-0576(10)80236-3.
- 21. Singh S S K, Abdullah S, Mohamed N A N. Reliability analysis and prediction for time to failure distribution of an automobile crankshaft. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2015; 17 (3): 408–415, https://doi.org/10.17531/ein.2015.3.11.
- 22. Snowden-Swan L. Transfer Efficiency and VOC Emissions of Spray Gun and Coating Technologies in Wood Finishing. Pacific Northwest Pollution Prevention Research Center 1992.
- Stępień Z. A study of factors influencing the formation of harmful deposits in the diesel engine injectors. Eksploatacja i Niezawodnosc Maintenance and Reliability 2017; 19 (3): 331–337, https://dx.doi.org/10.17531/ein.2017.3.3.

- 24. Wiechuła B M. The assessment of explosion risk in cabins during spraying coating powder. Eksploatacja i Niezawodnosc Maintenance and Reliability 2005; 7 (25): 3-15.
- 25. Wright S R, Bond J H. Hazardous waste Minimization of paint overspray via medialess dynamic particle filtration. Final Report INNOVATECH, INC, 25 Apr 97 -25 Jan 98.
- 26. Best Practice Guidelines for Vehicle Refinishing Issued to support European Union (Paints, Varnishes, Vehicle Refinishing Products and Activities), Regulations Environmental Protection Agency Office of Environmental Enforcement (OEE), 2012.
- 27. Isocyanate paint spraying, Safely managing spray booths and rooms. http://www.hse.gov.uk/pUbns/priced/hsg276.pdf (03.03.2018).
- 28. Archive of Techniki Systemów Aplikacyjnych Sp. z o.o.
- $29. \quad http://www.pandaspraybooth.com/pdf/filterInfo.pdf (16.03.2017).$
- 30. http://www.prowest.pl/cms/uploads/Filtry\_katalog.pdf (16.03.2017).

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# TWO PROBABILISTIC LIFE-CYCLE MAINTENANCE MODELS FOR THE DETERIORATING PAVEMENT

# DWA PROBABILISTYCZNE MODELE EKSPLOATACJI NISZCZEJĄCEJ NAWIERZCHNI DROGOWEJ

Pavement maintenance management poses a significant challenge for highway agencies in terms of pavement deterioration over time and limited financial resources to keep the road condition at an acceptable level. In this paper two probabilistic maintenance models are proposed and compared for pavement deterioration and maintenance processes to evaluate different maintenance strategies. Firstly, the states of pavement condition are defined using the features of different pavement maintenance works, instead of using the traditional method of cumulative service index rating. Secondly, a Markovian model is presented to describe the pavement deterioration and maintenance process with some constraints on the number of interventions, the effect of interventions and etc. But for the complex scenarios, such as non-Markovian deterioration, dependencies between the different types of interventions and the usage of emergency maintenance for roads when the required budget for maintenance is unavailable, a simulation-based Petri-net model is built up to investigate the whole life-cycle evolution. Two examples are used to illustrate and compare the proposed models to demonstrate the merits and disadvantages of each model and its applicable conditions.

Keywords: performance deterioration; pavement maintenance management; Markov process; Petri-net method.

Zarządzanie utrzymaniem nawierzchni stanowi poważne wyzwanie dla agencji eksploatacji autostrad, ponieważ stan nawierzchni wraz z upływem czasu ulega pogorszeniu, a środki finansowe potrzebne na utrzymanie jej w stanie używalności są ograniczone. W niniejszej pracy zaproponowano dwa probabilistyczne modele utrzymania nawierzchni drogowej. Modele porównywano w odniesieniu do procesów niszczenia nawierzchni oraz jej konserwacji, celem oceny różnych strategii eksploatacji. Na wstępie określono stan nawierzchni na podstawie charakterystyk wykonanych prac konserwacyjnych, zamiast korzystania z tradycyjnej metody oceny narastającego wskaźnika obsługi technicznej. Po drugie, przedstawiono model Markowa opisujący procesy niszczenia i konserwacji nawierzchni, z pewnymi ograniczeniami dotyczącymi liczby napraw, wyników napraw, itp. W przypadku złożonych scenariuszy obejmujących niszczenie jako proces niemarkowowski, opisanie zależności między różnymi typami napraw oraz korzystania z konserwacji awaryjnej dróg, w przypadkach gdy wymagany budżet na konserwację jest niedostępny, wymaga skonstruowania modelu sieci Petriego opartego na symulacji. Model ten pozwala na zbadanie ewolucji całego cyklu życia nawierzchni. W pracy przedstawiono dwa przykłady umożliwiające porównanie wad i zalet proponowanych modeli. Przykłady ilustrują także warunki zastosowania tych modeli.

*Słowa kluczowe*: pogorszenie charakterystyk; zarządzanie utrzymaniem nawierzchni; proces Markowa; metoda sieci Petriego.

# 1. Introduction

Highway infrastructure is not only the most valuable asset for most countries, but also the largest asset used daily by the majority of their residents, which can strongly affect their quality of life. With increasing demands to cut the cost of road maintenance and maintain and even improve road conditions under reduced financial investments, highways agencies are placing more focus on establishing an efficient pavement management system (PMS). For example, FHWA (Federal Highway Administration) in the United States established a policy in 1989 which required all the states to have a PMS for managing interstate and principal highways [23]. Over 60% local councils have established PMS in United Kingdom before 2009 [5]. One of the main functions of the PMS is to support asset management decisions when a cost-effective road maintenance strategy needs to be found. However, this is a difficult task to achieve since such a strategy will depend on a number of factors [10, 14], to name a few, the type and distress of pavement (such as rutting, cracking, ravelling and roughness, etc.), its location, climate and usage, effectiveness of pavement treatment technologies, etc. Therefore, over the last few decades a lot of research has been undertaken in the area of pavement deterioration and maintenance modelling. In general [2], pavement condition models can be divided into two categories: deterministic and probabilistic. In a deterministic model it is assumed that the pavement condition can be predicted as a single value on the basis of appropriate mathematical equations which relate the condition to a number of explanatory variables. For example, data on structural indicators [7], such as rutting and roughness, or service indexes [18], such as PSI (Present Serviceability Index), IRI (International Roughness Index) and CCI (Critical Condition Index), have been fitted to linear or nonlinear equations in order to predict the pavement condition. Such models cannot provide the PMS with a measure of uncertainty of future pavement condition, whereas probabilistic models can predict the condition as the probability of occurrence of a range of possible values, instead of a single

<sup>(\*)</sup> Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

value, and capture the uncertainty of pavement deterioration process and maintenance effects.

Markov model is a commonly used probabilistic state-based method for pavement condition, which can integrate several deterioration factors expressed in a transition probability matrix among discrete states [22]. It has been widely applied both in research and in practice for different types of pavement (rigid and flexible) to inform maintenance decisions at different levels of complexity (segment, project and network [9, 15, 24]). However, the underlying assumption of 'no memory' for Markov model is not suitable for the application in more realistic scenarios of pavement maintenance, such as the fact that maintenance decision for the current state can be determined not only by the current condition but also by history of recent interventions before the current condition is reached. Also, an exponentially increasing number of states with the growth of the number of pavement sections can result in difficulties in finding a solution [17]. Thus some simulation models have been proposed to describe more realistic scenarios of transportation deterioration and maintenance process. A probabilistic model [11] based on Monte Carlo simulation has been developed to evaluate the cost-reliability trade-off in a flexible maintenance strategy with the uncertainty of parameters and the effects of maintenance actions on pavement condition. Similarly, Hong and Prozzi[6] predicted pavement condition using Bayesian networks, which took account of three main factors of deterioration: structural indicators, environmental effects and traffic load, and Markov-chain Monte Carlo simulation was applied to estimate the parameter distribution. A simulation-based genetic algorithm (GA) approach was developed by Chootinan et al. [4] in order to plan maintenance activities over a planning period. A stochastic simulation was used to describe the uncertainty of future pavement condition, while the GA was used

### Nomenclature

to handle the large number of combinations of maintenance actions for a network level problem.

Due to its features the Petri net (PN) formulation with a Monte Carlo solution routine has been widely used to model the combined deterioration and maintenance processes [21]. For example[25], the PN method was used as a powerful analysis technique for the uncertainties in deterioration and maintenance process of multi-unit system, which has been combined with GA to get the solution of the optimal maintenance scheduling. Kowalski et al [12] extended the basic constructs of the high-level PN using the definition of immediate and timed transitions in order to model transportation system, where various factors such as redundancy, repair shop capacity and spare part inventory levels were discussed under different strategies in order to study effects of changing parameter values within the simulation. Prescott and Andrews [19] built a model of track maintenance processes using the PN method, which considered the order of interventions and opportunistic maintenance under the limitations on the number of maintenance machines available. Application examples [1, 8, 16] of PN include workflow of a business, asset management of a supply chain, maintenance processes of infrastructure systems and the production of an industrial plant. So far, no PMS methods published in literature considered the PN method as a tool for simulating complex processes of pavement deterioration and maintenance.

There are two major contributions of this paper in the area of pavement maintenance management. First of all, the states of pavement condition are defined according to the features of different pavement maintenance interventions, when the grouping into model states is based on the type and extent of pavement distress, instead of basing it on the cumulative service index. Secondly, the newly defined states can be used in a Markov model with some constraints and more realistic scenarios of pavement maintenance are proposed to be modelled

$s_i$ : pavement states, $i=0,1,1',2,2',3,4$	$P_{ij}$ : the transition probability between two states $s_i$ and $s_j$ at time <i>t</i> .
$r_1$ : the state threshold of routine repair	$c_i$ : the agency cost of intervention <i>i</i> , <i>i</i> =1,,4
$r_2$ : the state threshold of preventive repair	$t_{in}$ : the time spent on inspection
T: the inspection interval	$c_{ub}$ : the user cost when pavement remains in state $b$
$N_1$ : the maximum number of routine repair	$c_d$ : the delay cost caused by the closure of pavement repair
$N_2$ : the maximum number of preventive repair	$c_{in}$ : the cost of pavement inspection
$Y_t$ : the deteriorating process of pavement	$t_k$ : the decision epoch at $k^{th}$ inspection
L: the planning horizon	$CA_i^{m_1,m_2}$ : the mean agency cost calculated from time $E_i^{m_1,m_2}$ till the end of the planning horizon
$\lambda_i$ : the transition (deterioration) rate from state $s_0$ to $s_i$ , $i=1,1',2,2',3,4$	$CU_i^{m_1,m_2}$ : the user cost calculated from time $E_i^{m_1,m_2}$ till the end of the planning horizon
$\mu_i$ : the transition (repair) rate from state $s_i$ to $s_0$ , $i=1,,4$	$Q_{ibj}(T)$ : the mean operation time of the pavement in state <i>b</i> , where $i \le b \le j$ , during the interval $[0,T]$
$E_i^{m_1,m_2}$ : the time when the section of the pavement has been identified to be in state $s_i$ after $m_1$ routine repairs and $m_2$ preventive repairs	$L_i^{m_1,m_2}(T)$ : the mean time from time $E_i^{m_1,m_2}$ to the completion of the next renewal
$C_p$ : the long-term cost in the planning horizon	$L_p$ : the expected life-cycle time in the planning horizon
$N_{rr}\!\!:$ the number of routine repairs in the planning horizon calculated from the PN model	$N_{em}$ : the number of emergency maintenance works
N <sub>pr</sub> : the number of preventive repairs	N <sub>rec</sub> : the number of reconstructions
$N_{cm}$ : the number of corrective maintenance works	$D_i$ : the duration of staying in state <i>i</i> , <i>i</i> =3, 3' and 4
N <sub>in</sub> : the number of inspections	

using the PN method. Such scenarios include situations when the pavement deterioration cannot satisfy the "no-memory" assumption and may depend not only on the usage of the asset but also on the effects of maintenance works carried out previously, such as the history of the number and type of routine and preventive repairs. In addition, emergency repairs of pavement might need to be carried out while the required budget for planned maintenance is unavailable, and this common strategy (when there are increasing pressures to cut the cost of road maintenance) cannot be modelled using Markov model. Using the proposed methods different maintenance strategies can be compared in terms of long-term cost and the extended pavement design life in order to inform pavement management decisions.

The structure of this paper is as follows. In Section 2 the states of the pavement are defined according to the type and extent of pavement distress followed by the features of the relevant interventions. Two pavement maintenance models are built in Section 3, using the newly defined states in the Markov model and the PN model. Section 4 illustrates the results of the two models using two examples. First of all, the Markov model and the PN model have been solved for a number of simple scenarios to demonstrate the validity of the two models developed. Then a number of more complex scenarios have been used to demonstrate the flexibility of the PN model and the simulation method for maintenance planning. The sensitivity analysis has also been carried out in order to illustrate the influence of the main factors on the analysis. Some concluding remarks are given in Section 5.

## 2. The process of pavement deterioration and maintenance

The states in deterioration model are defined using a rating score of some service indexes. For example [10], the score of CCI can be grouped into five intervals from 0 to 100, where a range above 90 corresponds to excellent, 70-89 - good, 60-69 - fair, 50-59 - poor, 49 and below - very poor condition. However, the pavement distresses can be divided into three categories: structural deterioration (alligator cracking and rutting), environmental cracking (longitudinal/transverse cracking and edge cracking) and surface wear (ravelling/weathering and distortion). A service index like CCI can only represents the combination of several pavement distresses, which maybe not make the most of the information from the other distresses or maintenance process. According to highway maintenance manuals [10], a specific maintenance action can correspond to the different type of distress with different extent and severity. Further details of the grouping can be found in Appendix A. In addition, most PMS has relatively complete records on maintenance type and time rather than on pavement distresses. Some recent developments in railway track [3] and bridge asset management modelling [13, 19] illustrate how the states can be defined according to specific deterioration experienced and maintenance actions carried out to improve the usage of all collected information.

Therefore, In this paper it is proposed to group the types and severity of distress into four states according to decrease in pavement functionality and maintenance actions required, classified as routine repair (RR) ( $s_1$  – cracking treatment and patching), preventive repair (PR) ( $s_2$  – chip seal, slurry seal and micro-surfacing; thin overlay), corrective maintenance (CM) ( $s_3$  – mill and fill; mill and overlay) and reconstruction ( $s_4$ ). The state is revealed by periodic inspections; therefore, even if the transition occurs between two consecutive inspections, maintenance cannot be carried out until the inspection takes place. It is assumed that corrective maintenance and reconstruction restore the pavement to the new state, however, the routine and preventive repair can only improve the pavement to states  $s_1$  and  $s_2$ ' respectively, which are not the new states but better than former ones. Therefore, the deterioration level of the pavement can be defined by one of the states in  $S = \{s_0, s_1, s_2, s_1, s_2, s_3, s_4\}$ , where  $s_0$  represents pavement performance as new and no interventions are needed. The pavement starts in the new state and moves through the deteriorated states over time. Each maintenance strategy is defined by a vector  $(r_1, r_2, T, N_1, N_2)$ , where  $(r_1, r_2)$  denote the states for routine (RR) and preventive repairs (PR) respectively, T – the duration between two inspections, and  $(N_1, N_2)$  are the maximum number of routine and preventive repairs respectively. In general, three strategies are considered:

- (1) If  $N_1 = N_2 = 0$ , then no RR and PR on a section are possible; in the states  $s_3$  and  $s_4$  the CM or reconstruction is required respectively. In this case no routine or preventive works are carried out during the earlier levels of deterioration until corrective maintenance and reconstruction is necessary.
- (2) If  $N_1 = 0$ ,  $r_2 = 2$ , then the PR only (not the RR) on a section is required when the pavement is in state  $s_2$ ; in the following states CM and reconstruction is required. In this case preventive works (but not routine) are carried out during the earlier levels of deterioration, followed by corrective maintenance and reconstruction during the later levels of deterioration.
- (3) If r<sub>1</sub> = 1, r<sub>2</sub> = 2, N<sub>1</sub> ≠ 0, N<sub>2</sub> ≠ 0, then the RR and PR on a section are required (with the limitation on the maximum number) when the pavement is in state s<sub>1</sub> and s<sub>2</sub> respectively; in the following states CM and reconstruction is required. In this case all possible works are carried out during the pavement lifetime.

Each strategy can be evaluated in terms of its cost (agency and user cost [3]) and in terms of its effects on pavement condition. In this paper it is proposed to use the long-term cost and the lifetime of the pavement as two evaluation criteria. It is assumed that agency cost includes maintenance and inspection costs while user cost considers vehicle operation costs, such as fuel and lubrication consumption, tyre wear and vehicle repair costs, but not travel delay costs due to maintenance. The agency cost is influenced by planning the investment to keep roads at an acceptable level, and the user cost increases if the pavement deterioration increases. Benefits of the chosen strategy are then measured in terms of the additional years of usage of pavement.

# 3. Pavement maintenance models

Using the proposed scheme for defining pavement states in Section 2, two models have been developed in this paper. First of all, a Markov model is proposed and used to illustrate the process of pavement deterioration and maintenance with some constraints, such as the maximum number of repairs allowed and the effect of different repairs. Secondly, a PN model is proposed when more complex situations of road maintenance planning are considered, such as the non-Markovian deterioration process, the inclusion of the history on the previous interventions and the emergency repairs if the budget for expensive interventions is unavailable.

### 3.1. Markov model

If one can assume that the transition between any two states is at a constant rate, the deterioration process of the pavement can be characterized by a continuous-time Markov process  $\{Y_i\}_{i\geq 0}$  with state space S. If the planning horizon is denoted as L = nT,  $n \in N$ , then the sequence of inspections is denoted as  $\{T, 2T, ..., nT\}$ . At each inspection the state of the pavement will be identified and the interventions, which will restore the pavement to the new state, will be modelled according to the chosen strategy. The rate of deterioration and the rate of maintenance are defined as  $\lambda_i$  and  $\mu_i$  respectively, where *i* can be from 1 to 4. And the deterioration rates from  $s_0$  to  $s_1$ ' and  $s_2$ ' are assumed to be  $\lambda_{1'}$  and  $\lambda_{2'}$  respectively. A dynamic programming model can be built in order to evaluate the expected long-term cost and expected lifetime during the planning horizon. If the current decision epoch is  $t_k = kT, k \in \{1, 2, ..., n\}$ , the actions at  $t_k$  must be one of following: (1) do nothing, if i = 0, 1', 2' or  $i = 1, m_1 = N_1$  or  $i = 2, m_2 = N_2$ , i.e. the maximum number of routine repairs or preventive repairs has been reached; (2) repair the pavement with the specified intervention required by current state – routine repairs if  $i = 1, m_1 < N_1$ , preventive repairs if  $i = 2, m_2 < N_2$  corrective maintenance if i = 3 and reconstruction if i = 4. Then the long-term cost can be evaluated as  $C_i^{m_1,m_2}(t_k) = CA_i^{m_1,m_2}(t_k) + CU_i^{m_1,m_2}(t_k)$ . According to Bellman theorem [20], the cost can be calculated using the iterative approach described in Equations 1 and 2:

$$CA_{i}^{m_{1},m_{2}}(t_{k+1}) = \begin{cases} c_{in} + \sum_{j \in S} P_{ij}(T)C_{j}^{m_{1},m_{2}}(t_{k}), & i = 0, 1', 2' \text{ or } i = 1, m_{1} = N_{1} \text{ or } i = 2, m_{2} = N_{2} \\ c_{in} + c_{1} + \sum_{j \in S} P_{1'j}(T)C_{j}^{m_{1}+1,m_{2}}(t_{k}), & i = 1, m_{1} < N_{1} \\ c_{in} + c_{2} + \sum_{j \in S} P_{2'j}(T)C_{j}^{m_{1},m_{2}+1}(t_{k}), & i = 2, m_{2} < N_{2} \\ c_{in} + c_{3} + \sum_{j \in S} P_{0j}(T)C_{j}^{m_{1},m_{2}}(t_{k}), & i = 3 \\ c_{in} + c_{4} + \sum_{j \in S} P_{0j}(T)C_{j}^{0,0}(t_{k}), & i = 4 \end{cases}$$
(1)

$$CU_{i}^{m_{1},m_{2}}(t_{k+1}) = \begin{cases} \sum_{j \in S} P_{ij}(T) \left[ \sum_{b=i}^{4} Q_{ibj}(T) * C_{ub} + CU_{j}^{m_{1},m_{2}}(t_{k}) \right], & i = 0, 1, 2' \text{ or } i = 1, m_{1} = N_{1} \text{ or } i = 2, m_{2} = N_{2} \\ c_{d} / \mu_{1} + \sum_{j \in S} P_{1'j}(T) \left[ \sum_{b=1'}^{4} Q_{ibj}(T) * c_{ub} + CU_{j}^{m_{1}+1,m_{2}}(t_{k}) \right], & i = 1, m_{1} < N_{1} \\ c_{d} / \mu_{2} + \sum_{j \in S} P_{2'j}(T) \left[ \sum_{b=2'}^{4} Q_{ibj}(T) * c_{ub} + CU_{j}^{m_{1},m_{2}+1}(t_{k}) \right], & i = 2, m_{2} < N_{2} \\ c_{d} / \mu_{3} + \sum_{j \in S} P_{0j}(T) \left[ \sum_{b=0}^{4} Q_{ibj}(T) * c_{ub} + CU_{j}^{m_{1},m_{2}}(t_{k}) \right], & i = 3 \\ c_{d} / \mu_{4} + \sum_{j \in S} P_{0j}(T) \left[ \sum_{b=0}^{4} Q_{ibj}(T) * c_{ub} + CU_{j}^{0,0}(t_{k}) \right], & i = 4 \\ \end{cases}$$

$$(2)$$

When the transition rate from state  $s_i$  to  $s_j$ ,  $\lambda_i$ , is known, the transition probability,  $P_{ij}(t)$ , can be calculated by solving the Kolmogorov equation[20]. Let  $Q_{ibj}(T)$  represent the mean operation time of the pavement in state *b*, where  $i \le b \le j$ , during the interval [0,T], which

$$Q_{ibj}(T) = \int_0^T \frac{P_{ib}(t)P_{bj}(T-t)}{P_{ii}(T)} dt$$
(3)

Finally, the long-term cost can be computed as  $C_0^{0,0}(nT)$ .

can be calculated using Equation 3:

In addition, assume that  $L_i^{m_1,m_2}(T)$  is the mean time from time  $E_i^{m_1,m_2}$  to the completion of the next renewal. Due to the limitation on the maximum number of routine and preventive repairs, only the CM or reconstruction can result in the renewal of the pavement.

Therefore,  $L_i^{m_1,m_2}(T)$  can be calculated using Equation 4. Finally, the lifetime in the planning horizon can be calculated as  $L_0^{0,0}(T)$ .

Using this method, the long-run cost and the lifetime under different maintenance strategies can be evaluated.

$$L_{i}^{m_{1},m_{2}}(T) = \begin{cases} \sum_{j \in S} P_{ij}(T) \Big[ T + t_{in} + L_{j}^{m_{1},m_{2}}(T) \Big], & i = 0, 1', 2' \text{ or } i = 1, m_{1} = N_{1} \text{ or } i = 2, m_{2} = N_{2} \\ 1/\mu_{1} + \sum_{j \in S} P_{0j}(T) L_{j}^{m_{1}+1,m_{2}}(T), & i = 1, m_{1} < N_{1} \\ 1/\mu_{2} + \sum_{j \in S} P_{0j}(T) L_{j}^{m_{1},m_{2}+1}(T), & i = 2, m_{2} < N_{2} \\ 1/\mu_{3}, & i = 3 \\ 1/\mu_{4}, & i = 4 \end{cases}$$

$$(4)$$

This process of evaluation of different maintenance strategies is only possible if a number of simplifying assumptions are made. However, the assumption of the constant deterioration rate might not be always true in real-world applications, i.e. the rate of deterioration of the pavement will increase if the level of distress increases. Also the number and timing of routine repairs (crack sealing and patching) will influence the effectiveness of preventive repairs (micro-surfacing and thin overlay). In addition, there might be a situation when emergency maintenance works need to be carried out, such as pothole patching, if corrective maintenance is needed according to the state of the pavement but the resources for it are unavailable. In this case such actions would be a temporary solution until a more permanent treatment can be carried out. Overall, using Markov model it appears to be impossible to model a range of situations, commonly observed in the practice of pavement maintenance, and one possibility for solving the problem is to develop a simulation model.

#### 3.2. Petri-net model

The Petri-net (PN) method is commonly used to model the behaviour of dynamic systems in engineering, science and business context. The original concept of the PN is defined as a bi-partite directed graph with places and transitions linked by arcs. A place in the PN represents a particular state or condition of the system. A token presented inside the place indicates that the state of the system is true. A transition through the PN moves tokens from one place to another mimicking the dynamic behaviour of the system [19]. In the context of asset management, a PN can be used to replicate the processes of asset deterioration, inspection and maintenance. In this paper a PN model is proposed for modelling pavement deterioration and maintenance strategies, with the possibility to relax the assumptions needed for Markov approach.

#### 3.2.1. The description of PN model

The PN model as shown in Figure 1 is built up to illustrate how the complex process, described in Section 2, can be modelled in a probabilistic manner and the results used to support pavement maintenance decisions. Places from P0 to P4 represent the four states of the pavement and the transitions from T0 to T3 – the transitions between the neighboring states. These transitions will fire while sampling values from appropriate distributions, which can be obtained from historical data of pavement maintenance. Every state is revealed by inspection, which is modelled by the loop P5 $\rightarrow$ T4 $\rightarrow$ P6 $\rightarrow$ T5 $\rightarrow$ P5. If since the last inspection the pavement has degraded to one of the states, now it is revealed and the token is moved to a place which represents one of the four revealed states (places from P7 to P10). Then the complex scenarios which cannot be described by Markov model are illustrated in details.

(1) The dependency between the routine and preventive repair

The routine repair, such as crack sealing or patching, is the first line of defense in pavement maintenance. It is generally recommended to be carried out within two years after the pavement renewal. It is



Fig. 1. An overall PN model for pavement maintenance management

assumed that following this routine or preventive repair, the pavement returns to a better but not new state, i.e. the token is transferred to Place P1' or P2'. In addition, the routine repair is required to be carried out as a pretreatment in the preparation phase before the preventive repair, if there are some cracks or potholes in the pavement. For example, cracks of 1/4 inch or wider should be treated (using crack sealing) prior to the chip sealing. However, if the routine repair has been carried out within one year after the renewal, the pretreatment before the preventive repair is unnecessary. The dependency between the routine and preventive repair has been modelled in Figure 2a and 2b. In Figure 2a the place P13 is used to represent an event when the routine repair has been carried out after the last inspection before state P2 (which requires the preventive repair) is reached. Note that commonly the pavement maintenance annuals recommend that the inspection should be carried out at least once per year. This process of the routine repair also influences the process of the preventive repair, as



Fig. 2. Two PNs for the processes of routine (a) and preventive repairs (b)





Fig. 3. Two PNs for the introduction of the maximum number of routine (a) and preventive repairs (b)

shown in Figure 2b, when the transition T13, which represents a situation when the preventive repair should be performed after the pretreatment of the routine repair, is inhibited. The transition T12 will be enabled when the preventive repair without a pretreatment is possible.

With time some interventions can become ineffective after being carried out for a number of times. For example, the overlay (preventive repair) can be carried out only for a limited number of times until a certain thickness of the pavement is reached. Thus places P11 and P12 are used to record the number of times the routine and preventive repairs were carried out, as shown in Figure 2. Once the maximum number of the intervention is reached, N1 and N2 for the routine and preventive repair respectively, further repairs are inhibited.

In order to ensure that the deterioration process can continue in the model, two transitions T17 and T18 are used in Figure 3, also known as the reset transitions. Note that the reset transition is not a commonly used type of the transition in the PN method, as developed in [21]. In this model the reset transitions are used to represent the situation when, for example, the routine repair cannot be carried out (since the maximum number of repairs is reached) and all the tokens from the place P11 are removed in Figure 3a, so that the process of carrying out the routine repairs can restart after the next inspection. A similar situation is described in Figure 3b when the preventive repairs are considered.

#### (2) The emergency repairs if the resources are unavailable

If the corrective maintenance is needed, the significant levels of pavement deterioration need to be treated quickly to avoid further deterioration and resulting hazardous situations. If the resources for

> the corrective maintenance are unavailable (due to poor planning or unforeseen conditions, such as bad weather), a temporary treatment, known as the emergency maintenance (EM), should be performed in the meantime. For example, if large potholes appear in the section an intervention of hand patching can be carried out in order to hold the surface together until the mill & fill treatment (corrective maintenance) can be performed. This situation is modelled in Figure 4. If the budget is available to carry out the corrective maintenance, the places P9 and P15 are marked and after the repair the pavement returns to the new state. Otherwise, the emergency repair is carried out marking the place P3', which describes an intermediate state before it happens, and using the repair transition T20 to return to the state, denoted by P3, where corrective maintenance is necessary, but it can be carried out at a later date.

#### 3.2.2. The analysis of PN model

As in Section 3.1, the PN model is used to evaluate the long-term cost and lifetime. The model is solved using a Monte Carlo simulation, when each simulation corresponds to a virtual experiment when one life history of the section evaluated throughout the planning horizon. For example, the long-term cost  $C_p$  in the planning horizon can be calculated using Equation 5:

$$C_p = c_1 N_{rr} + c_2 N_{pr} + c_3 N_{em} + c_3 N_{cm} + c_4 N_{rec} + \sum_{b \in \{3,3',4\}} c_{ub} D_b + c_{in} N_{in}$$
(5)



Fig. 4. A PN for the processes of corrective maintenance and reconstruction

First of all, the number of different interventions and inspections are obtained from the PN model, by recording the number of times when relevant transitions have been enabled, such as T10 and T11 for the routine repair. These numbers are multiplied by the agency cost for each intervention and inspection. Secondly, the duration of being in the state that influences the user cost are obtained, by recording the time when relevant places have been marked for, such as P3 for corrective maintenance. These durations are multiplied by the user cost in each state. Note that the statistics are collected over the planning period.

In addition, other results can be obtained from the PN model, such as the number of preventive repairs that were carried out with or without a pretreatment, the number of times when the budget has been exceeded, etc. Such statistics can provide the decision maker with detailed information, impossible to obtain using the analytical approach, about each strategy of pavement maintenance and support their investment decisions.

# 4. Numerical application

The two models developed in Section 3 are solved using numerical values for the parameters. For example, the length of the pavement section is assumed to be 1 km and the planning horizon is 50 years. Example 1 demonstrates that the results of the two models (Markov and PN) agree, if some complex scenarios cannot be considered in the PN illustrated in Figure 1; Example 2 demonstrates how the PN model can be useful in analyzing the maintenance strategies that are more complex than those described in the Markov model.

### 4.1. Example 1

#### 4.1.1. Model implementation

The values of the deterioration and cost parameters are listed in Table 1. According to pavement maintenance manuals[10] the recommended frequencies of the crack sealing (RR), thin overlay (PR), mill & fill (CM) and reconstruction are once in 2 years, once in 7 years, once in 15 years and once in 30 years respectively. The effect of cracking sealing maybe remain 1 year and thin overlay can extend the life of pavement about 5.5 years. For illustration purposes in this paper these frequencies have been used to derive the deterioration rates from the new state to a deteriorated state that requires each maintenance action considered. The intervention cost and the mean time to its completion increase the worse the pavement becomes. It is assumed that the user cost is considered only if the states of the pavement need the corrective maintenance  $(s_3)$  or reconstruction  $(s_4)$ , otherwise, they are ignored. The cost and duration of the yearly inspection is assumed to be constant at each state of deterioration. These assumptions have been taken to simplify the calculations; however, they can be relaxed to represent different scenarios of maintenance if required. Note that the time to the next level of deterioration and the time to the completion of the intervention follow the exponential distribution, necessary for Markov model.

A number of different maintenance strategies are consider in Table 2 and analyzed below.

The Markov model has been solved using an analytical approach and the PN model has been simulated for 3000 simulations

State	from $s_0$ to $s_1$ '	from $s_0$ to $s_2$ '	from s <sub>0</sub> to s <sub>1</sub>	from s <sub>0</sub> to s <sub>2</sub>	from s <sub>0</sub> to s <sub>3</sub>	from s <sub>0</sub> to s <sub>4</sub>
Deterioration rate (per day)	0.00278	0.00185	0.00139	0.00035	0.00019	0.00009
Intervention cost (\$)	0	0	200	1500	3000	7000
State	<i>s</i> <sub>1</sub> '	<i>s</i> <sub>2</sub> '	<i>s</i> <sub>1</sub>	<i>s</i> <sub>2</sub>	<i>s</i> <sub>3</sub>	<i>S</i> <sub>4</sub>
Mean time of an intervention (day)	0	0	0	7	15	60
User cost (\$/day)	0	0	0	0	10	50
Inspection cost (\$)				1	.0	
Inspection duration (day)				0	.1	

#### Table 1. Input parameters for Example 1

Table 2. Pavement maintenance strategies

Strategy	rį	$r_2$	$N_1$	<i>N</i> <sub>2</sub>	T (year)	Description
1	3	3	0	0	1	No RR and PR, CM (in state $s_3$ ) and reconstruction (in state $s_4$ )
2	2	3	1	0	1	Once RR ( $s_1$ ), No PR, CM ( $s_3$ ) and reconstruction ( $s_4$ )
3	2	3	2	0	1	Twice RR ( $s_1$ ), No PR, CM ( $s_3$ ) and reconstruction ( $s_4$ )
4	2	2	0	1	1	No RR, once PR ( $s_2$ ), CM ( $s_3$ ) and reconstruction ( $s_4$ )
5	2	2	0	2	1	No RR, twice PR ( $s_2$ ), CM ( $s_3$ ) and reconstruction ( $s_4$ )
6	1	2	1	1	1	Once RR ( $s_1$ ), once PR ( $s_2$ ), CM ( $s_3$ ) and reconstruction ( $s_4$ )
7	1	2	2	1	1	Twice RR ( $s_1$ ), once PR ( $s_2$ ), CM ( $s_3$ ) and reconstruction ( $s_4$ )
8	1	2	1	2	1	Once RR ( $s_1$ ), twice PR ( $s_2$ ), CM ( $s_3$ ) and reconstruction ( $s_4$ )
9	1	2	2	2	1	Twice RR ( $s_1$ ), twice PR ( $s_2$ ), CM ( $s_3$ ) and reconstruction ( $s_4$ )



Fig. 5. The results of the long-term cost (a) and the lifetime (b) in Example 1

for each strategy. Note that 3000 simulations gave the convergence of the simulation results, as demonstrated in Section 4.2. Two outputs have been recorded, the long-term cost and the lifetime, as shown in Figure 5. The curves from the two models match well and can be used to validate the correctness of the implementation of the models, with some marginal differences between the long-term cost curves for some strategies. These differences can be explained by using an approximation of the numerical integral when computing  $Q_{ibj}(T)$  in Markov model.

It can be seen that the long-term cost decreases when the routine and preventive repairs are introduced instead of using the corrective maintenance and reconstruction only, i.e. considering the strategies from 1 (no RR and PR) to 9 (both RR and PR implemented twice). At the same time, the lifetime increases, i.e. the pavement lasts longer if the routine and preventive repairs are carried out while the pavement is in an acceptable condition (state  $s_1$  and  $s_2$ ), instead of relying on the major interventions only applied in the more critical states (state  $s_3$  and  $s_4$ ). In addition, it is possible to analyze whether the routine repairs (cheap and quick) or the preventive repairs (expensive and long) are more effective. According to the results in Example 1 it can be seen that the strategy with a higher number of the preventive repairs than the routine repairs (for example, strategy 8,  $N_1$ =1 and  $N_2$  = 2) results in the same cost and a longer lifetime than the strategy with a lower number of the preventive repairs (for example, strategy 7,  $N_1 = 2, N_2 = 1$ ).

### 4.1.2. Sensitivity analysis

In order to determine the effects on the long-term cost and lifetime resulted in by using the different parameters in the model, their sensitivity analysis has been carried out. For the illustration purposes only the results from one of the models (the PN model) has been used in this section.

#### (1) User cost

If the user cost is not included in the analysis, i.e. each strategy is evaluated in terms of agency cost only, it can be seen that it is hard



Fig. 6. The results of the long-term cost with the user cost and without the user cost

to distinguish between the different strategies of pavement maintenance and hardly any benefits can be seen from the strategies that allow smaller and more frequent repairs in order to reduce the long-term cost, as shown in Figure 6. Therefore, the user cost should be included in the analysis. Note, that the user cost does not influence the lifetime in this study, therefore, no sensitivity analysis on this model output is carried out.

#### (2) Cost of preventive repairs

The chosen value of the preventive repair cost can influence the comparison of the strategies that consider a different number of the routine repairs and preventive repairs, say strategy 7 (twice RR and once PR) and strategy 8 (once

RR and twice PR). In the analysis presented in this section it is assumed that the cost of preventive repair is \$1500, as stated in Table 1, and the long-term cost of strategies 7 and 8 are the same, as shown in Figure 7.



Fig. 7. Influence of cost of preventive repairs to the long-term cost for the strategies 7 and 8

If the cost of the preventive repair can be reduced, the longterm cost for strategy 8 (with a higher number of preventive repairs) is lower than for strategy 7 (with a lower number of preventive repairs). Alternatively, if the cost is higher, an advantage in terms of the long-term cost can be seen from strategy 7 instead of strategy 8, as shown in Figure 7. Note that as for the analysis of the user cost above, the change in the preventive repair cost has no influence on the life-time cycle of the pavement. Therefore, in terms of the lifetime strategy 8 is better than strategy 7 (as shown in Figure 5b) despite of the increase in the preventive repair cost.

#### (3) Inspection interval

The inspection interval T is an important factor that can influence maintenance strategies. In Figure 8, the long-term cost and the lifetime are considered when the inspection interval is one year (Inspection 1) and 6 months (Inspection 2). When the inspections are carried out more frequently (Inspection 2), the states of the pavement are revealed and the relevant interventions carried out more frequently.

Therefore, in this study it can be seen that the additional cost of inspection due to more frequent inspections (Inspection 2) results in a lower long-term cost (Figure 8a) than in the situation of less frequent inspections (Inspection 1). In terms of the lifetime (Figure 8b), the situation with more frequent inspections gives an increase (although only a marginal one) for the strategies that consider a certain number of routine repairs and preventive repairs, such as strategies 7 and 8, instead of mainly relying on the corrective maintenance and reconstruction.

State	from $s_0$ to $s_1$	from s <sub>1</sub> ' to s <sub>1</sub>	from $s_2$ 'to $s_1$	from $s_0$ to $s_2$	from $s_0$ to $s_3$	from $s_0$ to $s_4$	from $s_{3'}$ to $s_3$
Weibull parameter $\beta$	1.3	1.2	1.2	1.5	1.8	2.2	2
Weibull parameter $\eta$ (days)	720	360	540	2880	5400	10800	360
State	<i>s</i> <sub>1</sub>	<i>s</i> <sub>1</sub>	<i>s</i> <sub>1</sub>	<i>s</i> <sub>2</sub>	<i>s</i> <sub>3</sub>	s <sub>4</sub>	s <sub>3'</sub>
Intervention cost (\$)	200	200	200	1500	3000	7000	200
Mean time to complete an interven- tion (day)	1	1	1	7	15	60	1
User cost (\$/day)	0	0	0	0	10	50	8
Inspection cost (\$)				10			
Inspection duration (day)				0.1			
Mean of the budget planning period (year)							





Fig. 8. The results of the long-term cost (a) and the lifetime (b) for the two values of the inspection interval

### 4.2. Example 2

### 4.2.1. Model implementation

In this example, the PN model in Figure 1 is used to obtain the results of the analysis. A number of assumptions have been made. A two-parameter Weibull distribution has been assumed to describe the time to reach each deteriorated state, as shown in Table 3. Note that in addition to the six states considered in Example 1, state 3' is introduced which is used to model the state obtained after an intervention of emergency repairs. The parameters of the Weibull distribution have been assumed and the scale parameter  $\eta$  was chosen according to the recommended frequencies of maintenance actions, used in Example 1.

Since the deterioration rate of the pavement is to increase with time (due to the wear-out characteristic), the shape parameter  $\beta$  is chosen to be greater than 1 and it is increasing with each state, as given in Table

3. The intervention costs and the mean time to complete an intervention are assumed to be as in Example 1, including the cost of the emergency repair and the time to complete it (given in the final column) to be equal to the parameters of the routine repair (given in the second column). Since the EM is used to recover from some serious damage using a temporary solution and cannot improve the performance of the pavement, the user cost for the EM has been assumed to be similar to the value during the CM. According to pavement maintenance manuals [10] the budget planning period is assumed to be 10 years, since it is recommended to carry out the CM every 10 to 15 years. The time to the end of the budget planning period is assumed to follow the exponential distribution with  $\lambda = 0.1$ . Note that in this paper the time to the next level of deterioration follows the Weibull distribution, and the time to the completion of the intervention follows the exponential distribution. However, there are no limitations on the type of distribu-



Fig. 9. The relationship between the mean duration of staying in the different states and the number of simulations



Fig. 10. The relationship between the average number of interventions in planning horizon and the number of simulations

tion to be used, which could be derived from the analysis of historical data of pavement deterioration and maintenance records.



Fig. 11. The long-term cost and lifetime in Example 2

Using the Monte Carlo simulation method to solve the PN model in Figure 1, a number of statistics have been collected in order to test convergence of the results. These include the duration of staying in particular states (Figure 9) and the number of interventions (Figure 10) over the planning horizon of 50 years. Note

that strategy 9 was chosen for the illustration purposes in Figures 9 and 10. Based on these results the number of simulations for each strategy has been chosen to be 3000, as the outputs of the model have converged after this number of simulations.

Further conclusions about the chosen strategy (strategy 9 in this case) could be drawn from Figure 9. For example, if the last three states (state  $s_3$ ,  $s_3$ , and state  $s_4$ ) are considered as hazardous and potentially causing road safety risks, over the planning horizon the pavement stays in these states for around 350 days if strategy 9 is implemented. In other words, the probability to stay in a hazardous state (if strategy 9 is implemented) is under 2%. This example

illustrates one of the additional criteria (in addition to the long-term cost and the lifetime) of comparing different strategies using the PN method, which was not possible using the Markov method. In addition to the long-term cost and the lifetime, such conclusions on other outcomes of the model can also be used to inform maintenance decisions.

The long-term cost and the lifetime under different strategies (as listed in Table 2) are given in Figure 11 with 3000 simulations. As in Example 1, it can be seen the routine repairs and preventive repairs can reduce the long-term cost and extend the lifetime of the pavement,

since the strategies with a higher number of these (such as strategies 7, 8 and 9) result in lower cost and greater lifetime.

### 4.2.2. Sensitivity analysis

The PN model in Figure 1 has been developed with the focus of illustrating the possibility to model the emergency maintenance and the dependencies between the routine and preventive repairs, which were impossible to take account of using the Markov model. Therefore, the budget planning period and the inspection interval, as the two parameters that influence these maintenance actions, have been chosen in the sensitivity analysis.

### (1) The budget planning period

The chosen value of the budget planning period, which affects how often the corrective maintenance can be carried out or the emergency repairs are needed due to budget limitations, can influence the longterm cost (Figure 12a) and the lifetime (Figure 12b) for the different strategies. Three mean values of this period were chosen: 5 years, 10 years and 15 years. If the period is shortened from 15 years to 5 years, savings in the long-term cost are observed for strategy 1, where only the corrective maintenance and reconstruction are possible.

For the other strategies, saving in the long-term cost will become less apparent if this period is reduced. This could be due to a larger number of emergency repairs required during the less frequent budget planning process, which offset the cost saving caused by the routine and the preventive repairs. The larger the budget planning period the higher the lifetime, since a larger number of emergency repairs delay the occurrence of corrective repairs and reconstruction and delay the renewal. If both criteria are of importance (minimize the cost and maximize the lifetime) the value for the budget planning period needs to be chosen carefully.



Fig. 12. The results of the long-term cost (a) and the lifetime (b) for the three values of the budget planning period

(2) Inspection interval

In Figure 13, the long-term cost and the lifetime are considered when the inspection interval is 1.5 years (inspection 1), 1 year (inspection 2) and 6 months (Inspection 3). As in Example 1, when the inspections are carried out more frequently, the states of the pavement are revealed and the relevant interventions carried out more frequently.

Therefore, in this study it can be seen that more frequent inspections (Inspection 2) result in a lower, long-term cost (Figure 13a) and longer, although marginally, lifetime (Figure 13b) than in the situation of less frequent inspections (Inspection 1), especially for the strategies



Fig. 13. The results of the long-term cost (a) and lifetime (b) for the two values of the inspection interval

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with fewer routine and preventive repairs. If the frequency of inspections continues to increase (inspection 3), the savings on the longterm cost become smaller and the lifetime even decreases than in the situation with less frequent inspections (inspection 2). The reduction in the savings on the cost is caused by an increase of cost due to additional inspections, whereas a shorter lifetime could be explained by an increased number of corrective maintenance actions when the poor state of the pavement is revealed (and rectified) more often. When choosing the frequency of the inspection interval, the balance between the long-term cost and the lifetime should be investigated carefully.

### 5. Conclusions

Efficient pavement management is of great importance for the governing transport bodies in terms of maintenance and reconstruction costs and pavement deterioration. This study is on modelling pavement deterioration and maintenance processes in order to evaluate different strategies for pavement management.

An analytic model based on Markov process and a simulation model based on Petri-net have been developed to support pavement management decisions under different scenarios. The results from two models are compared in a numerical example to evaluate a number of characteristics suitable for comparing different pavement management strategies, such as the long-term cost and the lifetime of the pavement. For the values of the different parameters chosen it has been demonstrated that the strategies where the routine repairs and preventive repairs are carried out while the pavement is still in the good state can result in savings in the long-term cost and extend the pavement design life, in comparison to the strategies where the corrective maintenance and reconstruction only are carried out (when the more critical states of the deterioration have been reached). Additional outputs of the PN model can be obtained, such as the time spent in critical pavement states under a chosen strategy, and used to compare different maintenance approaches.

The sensitivity analysis has been carried out in order to investigate the effects of the main factors used in the analysis, such as the user cost, the cost of preventive repairs, the inspection interval and the budget planning period. It has been demonstrated how these main factors influence the results of the analysis and should be carefully considered when using the proposed method to inform maintenance decisions. One way of testing a range of parameter values is to formulate and solve an optimization routine where such values can be analyzed in an automatic way.

In future works we could extend the models by using in-field data to define the probability distributions for describing the process of pavement deterioration and the effect of different interventions, which are more accordant with practical circumstances. Further complexity in road maintenance practice and system-level road maintenance optimization can be analyzed by improving the simulation model with coloured PN method.

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### References

- Aalst W M P. The Application of Petri Nets to Workflow Management. Journal of Circuits, Systems and Computers 1998; 8: 21-66, https:// doi.org/10.1142/S0218126698000043.
- 2. Anastasios M L, Pavan K T. An overview and a case study of pavement performance prediction. International Journal of Pavement Engineering 2013; 14(7): 629-644, https://doi.org/10.1080/10298436.2012.715644.
- 3. Andrews J D. A Modeling Approach to Railway Track Asset Management. Proceedings of the Institution of Mechanical Engineers. Part F: Journal of Rail and Rapid Transit 2012; 1: 1-18.
- 4. Chootinan P, Chen A, Horrocks M R, Bolling D. A Multi-year Pavement Maintenance Program using a Stochastic Simulation-based Genetic Algorithm Approach. Transportation Research Part A: Policy and Practice 2006; 40: 725-743, https://doi.org/10.1016/j.tra.2005.12.003.
- FHWA, Transportation Research Program Administration in Europe and Asia, Technical Report, Federal Highway Administration, U.S. Department of Transportation, 2009:3-7.
- Hong F, Prozzi J A. Estimation of Pavement Performance Deterioration using Bayesian Approach. Journal of Infrastructure Systems 2006; 12: 77-86, https://doi.org/10.1061/(ASCE)1076-0342(2006)12:2(77).
- Iken M, Brandhorst H, Korsgren O, Brandhorst D. Evaluating the cost effectiveness of flexible rehabilitation treatments using different performance criteria. Journal of Transportation Engineering 2009; 135(10): 753-763, https://doi.org/10.1061/(ASCE)TE.1943-5436.0000041.
- 8. Jingyu S, Derren P. A hierachical colored Petri net model pf fleet maintenance with cannibalisation. Reliability Engineering and System Safety 2017; 168: 290-305, https://doi.org/10.1016/j.ress.2017.05.043.
- 9. Jinwoo L, Samer M. A joint bottom-up solution methodology for system-level pavement rehabilitation and reconstruction. Transportation Research Part B 2015; 78:106-122, https://doi.org/10.1016/j.trb.2015.05.001.
- 10. Johanns M, Craig J. Pavement maintenance manual. Nebraska: Department of Road, 2002:5-10.
- 11. Jui S C, Thanh S L. Reliability-based performance simulation for optimized pavement maintenance. Reliability Engineering and System Safety 2011; 96:1402-1410, https://doi.org/10.1016/j.ress.2011.05.005.
- 12. Kowalski M, Magott J, Nowakowski T, Werbinska W S. Analysis of Transportation system with the use of Petri nets. Eksploatacja i Niezawodnosc Maintenance and Reliability 2011; 1(49): 48-62.
- Le B, Andrews J D. Modelling Railway Bridge Asset Management. Proceedings of the Institution of Mechanical Engineers. Part F: Journal of Rail and Rapid Transit 2013; 2: 1-13, https://doi.org/10.1177/0954409713490924.
- Levulyte L, Zuraulis V, Sokolovskij E. The research of dynamic characteristics of a vehicle driving over road roughness. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2014; 16(4): 518-525.
- 15. Li N, Xie W C, Haas R. Reliability-based Processing of Markov Chains for Modeling Pavement Network Deterioration. Transportation Research Record 2010; 1524: 203- 213, https://doi.org/10.3141/1524-24.
- Liu R, Kumar A, Aalst W. A Formal Modeling Approach for Supply Chain Event Management. Decision Support Systems 2007; 43: 761-778, https://doi.org/10.1016/j.dss.2006.12.009.
- 17. Marzio M, Enrico Z., Luca P. Condition-based maintenance optimization by means of genetic algorithms and Monte Carlo simulation. Reliability Engineering and System Safety 2002; 77: 151-166, https://doi.org/10.1016/S0951-8320(02)00043-1.

- Prasad J R, Kanuganti S, Bhanegaonkar P N, Sarkar A K, Arkatkar S. Development of Relationship between Roughness (IRI) and Visible Surface Distress: A Study on PMGSY Roads. Procedia-Social and Behavioral Science 2013; 104: 322-331, https://doi.org/10.1016/j. sbspro.2013.11.125.
- Prescott D R, Andrews J D. A Track Ballast Maintenance and Inspection Model for a Rail Network. Proceedings of the Institution of Mechanical Engineers. Part F: Journal of Rail and Rapid Transit. 2013, 227: 251-266, https://doi.org/10.1177/1748006X13482848.
- Puterman M L. Markov Decision Process: Discrete Stochastic Dynamic Programming. 2nd edition. New Jersey: John Wiley & Sons Press. 2004.
- 21. Schneeweiss W G. Tutorial: Petri nets as a graphical description medium for many reliability scenarios. Reliability, IEEE Transactions on, 2001; 50(2): 159-164, https://doi.org/10.1109/24.963123.
- 22. Sugier J, Anders G J. Modelling and evaluation of deterioration process with maintenance activities. Eksploatacja i Niezawodnosc Maintenance and Reliability 2013; 15(4): 305-311.
- 23. U.S. Department of Transportation, Transportation in the United States A Review. New York: Bureau of Transportation Statistics, 1997:1-2.
- 24. Xueqing Z, Hui G. Road maintenance optimization through a discrete-time semi-Markov decision process. Reliability Engineering and System Safety 2012; 103: 110-119, https://doi.org/10.1016/j.ress.2012.03.011.
- 25. Zhang T, Cheng Z, Liu YJ, Guo B. Maintenance scheduling for multi-unit system: a stochastic Petri-net and genetric algorithm based approach. Eksploatacja i Niezawodnosc Maintenance and Reliability 2012; 14(3): 256-264.

# Appendix 1

The selection of interventions can depend on a number of factors, such as the type, severity and extent of distress, traffic volume and climate conditions, and realized by decision matrix or decision tree as listed in Table A.1. Possible pavement interventions include pavement crack treatment, patching, chip seal, micro-surfacing, overlay, fill & mill, reconstruction and etc.

	low	7	moder	rate	High	
Flexible pavement distress	Occasional	Frequent	Occasional	Frequent	Occasional	Frequent
Alligator cracking	3	3	4	4	6	6
Longitudinal cracking	2	2	4	4	6	6
Rutting	1	1	5+4	5+4	7	7
Transverse cracking	2	2	4	4	4	4
Random/block cracking	2	2	4	4	7	7
Raveling/weathering	3	3	4	4	7	7
Edge cracking	2	2	6	6	6	6
Distortion	1	1	5	5	5	5
Excess asphalt	1	1	4	4	5+4	5+4

Table A.1 maintenance action matrix for the different distresses

1: do nothing, 2: crack seal/fill, 3: fog seal, 4: chip seal/armor coat, 5: mill, 6: overlay , 7: mill&fill

Extent of distress: occasional- area or length affected<30%, frequent- area or length affected>=30%

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# A STATISTICAL DATA-BASED APPROACH TO INSTABILITY DETECTION AND WEAR PREDICTION IN RADIAL TURNING PROCESSES

# METODA WYKRYWANIA NIESTABILNOŚCI I PRZEWIDYWANIA ZUŻYCIA W PROCESACH TOCZENIA PROMIENIOWEGO W OPARCIU O DANE STATYSTYCZNE

Radial turning forces for tool-life improvements are studied, with the emphasis on predictive rather than preventive maintenance. A tool for wear prediction in various experimental settings of instability is proposed through the application of two statistical approaches to process data on tool-wear during turning processes: three sigma edit rule analysis and Principal Component Analysis (PCA). A Linear Mixed Model (LMM) is applied for wear prediction. These statistical approaches to instability detection generate results of acceptable accuracy for delivering expert opinion. They may be used for on-line monitoring to improve the processing of different materials. The LMM predicted significant differences for tool wear when turning different alloys and with different lubrication systems. It also predicted the degree to which the turning process could be extended while conserving stability. Finally, it should be mentioned that tool force in contact with the material was not considered to be an important input variable for the model.

Keywords: radial turning, tool-life improvement, instability detection, wear prediction, Linear Mixed Models.

Badano siły występujące w procesie toczenia promieniowego. Celem badań było wydłużenie żywotności narzędzi tokarskich, przy czym główny nacisk kładziono na konserwację predykcyjną, a nie zapobiegawczą. Zaproponowano technikę prognozowania zużycia w różnych warunkach eksperymentalnych niestabilności, która polega na zastosowaniu metod statystycznych do przetwarzania danych dotyczących zużycia narzędzi podczas procesów toczenia. Wykorzystano dwie metody statystycznę: analizę z zastosowaniem reguły trzech sigm oraz analizę głównych składowych (PCA). Do prognozowania zużycia zastosowano liniowy model mieszany (LMM). Omawiane statystyczne podejścia do wykrywania niestabilności generują wyniki o dopuszczalnej dokładności, na podstawie których można formułować opinie eksperckie. Dane te można wykorzystywać do doskonalenia przetwarzania różnych materiałów poprzez monitorowanie w trybie on-line. W przedstawionych badaniach, LMM pozwolił przewidzieć znaczące różnice w zużyciu narzędzia podczas toczenia różnych stopów przy zastosowaniu różnych systemów smarowania. Umożliwił także prognozowanie stopnia, w jakim proces toczenia można przedłużać zachowując jego stabilność. Na koniec należy wspomnieć, że nie brano pod uwagę siły generowanej w kontakcie narzędzia z materiałem jako istotnej zmiennej wejściowej dla modelu.

*Słowa kluczowe*: toczenie promieniowe, poprawa żywotności narzędzi, wykrywanie niestabilności, predykcja zużycia, liniowe modele mieszane.

## 1. Introduction

New lighter and thinner alloys may be found in innovative aerospace, rail, and automotive components, among other industrial products. Generally known as superalloys, these materials can withstand higher temperatures and mechanical stress levels than ordinary alloys and are designed to reduce consumption and to increase productivity.

Superalloys are categorized as hard turning materials with a hardness index of at least 45 on the Rockwell C-scale *HRC*. The process of turning such alloys, produces high mechanical and thermal stress on cutting tool inserts, which influence cutting force, tool wear, surface integrity, and the accuracy of machining processes.

Although these materials in themselves will entail process instability, monitoring of tool conditions can detect both material and process-related instabilities. Reliable predictions can therefore be made using the same data sets. Process instabilities are often recorded at increased vibratory amplitudes, provoking undesired tool failures among other events that can damage both the workpiece and the machine tool [13].

Tool condition monitoring can track tool wear and thereby predict the Remaining Useful Life (RUL) of the tool, a very important issue for rapid machining processes involving superalloys. Together with the detection of instability, tool monitoring provides a valuable data source for improving the efficiency of superalloy turning processes.

In this paper, cutting-force signals are studied for the detection of instabilities during the hard-turning process and a tool-wear prediction model is proposed. The three superalloys tested in this study were as follows: *Inconel 718, Haynes 282* and *Waspalloy*.

The structure of this paper will be as follows. In Section 2, related work on radial turning process optimization, tool-wear prediction, and the improvement of tool life will be discussed. In Section 3, the industrial application will be explained and, in Section 4, the methodology used to detect instabilities and to predict tool wear. The results will be presented in Section 5. Finally, the conclusions will be discussed in Section 6.

# 2. Related Work

Many investigators have been exploring ways of predicting cutting-tool behaviors RUL, by establishing the length of time certain tooling processes will withstand wear [1]. RUL is the analysis of the remaining working time and number of executions of a tool, at a particular working age. The resulting information is used to predict whether the tool can still machine the piece to an acceptable finish. [15] developed a proportional hazard model for the remaining useful life of 25 identical tools during the turning of titanium metal matrix composites. The remaining useful life curves were developed for two different machining conditions: cutting speed and feed rate. [9] analyzed tool wear in the finish turning of AISI 1045 steel under different cooling conditions, to conclude that minimum quantity cooling lubrication (MQCL) provided significant improvements in the wear rate of the cutting tool and its productivity. [7] estimated the RUL of a bearing process with artificial neural network models that produced better bearing failure performance predictions. [19] compared multiple machine learning algorithms for tool-wear prediction and concluded that Random Forest generated higher accuracy than Artificial Neural Networks and Support Vector Regression. [11] developed mathematical models for describing surface finish and flank wear, employing multiple linear regression analysis during ceramic-tool machining of AISI-D2 steel. The nose geometry of the cutting tool strongly influenced the productivity and surface finish of the hard-turning process. [6] developed an online Neural Network model for tool-wear monitorization based on force ratio and cutting conditions. The algorithm was successfully verified during turning. [12] estimated tool conditions by applying neuro-fuzzy techniques, which yielded the best results for tool-wear estimation with cutting force and machining time variables. [20] developed a model based on particle-swarm optimization that fitted better than the back-propagation neural network for tool-life prediction.

Although tool-life prediction and *RUL* estimation are important in machining processes, stability is also one of the main topics for achieving the aim of obtaining good quality pieces, due to the fact that even if the remaining useful life of the tool is good, an instability may cause a machine failure. On this topic, [14] proposed a linear stability analysis in the frequency domain based on cutting forces. [4] developed a linear model based on the root locus method, called a chatter model for predicting stability in hard-turning processes. [17] proposed a method for measuring the stability of cutting processes that applied the power-spectrum density of dynamic cutting forces.

As may be seen from this literature review, many technologies have been developed over the years to predict tool wear, to improve tool life, and to detect stability during machining processes. Most of these technologies have been applied to a particular fault and have yielded good results for both stability and wear prediction. A hybrid mix of both predictive approaches is proposed in this paper, which will enable better prediction for stable tests and will prevent possible failure modes related to instability.

# 3. Industrial Application

This study is based on a radial turning process, applied to nickelbased superalloys. Even though only nickel-based superalloys enter into the case study (*Waspalloy, Inconel 718* and *Haynes*), the chemical composition of the superalloys differs slightly. Cutting tests were conducted at 30 m/min cutting speed, with a depth of cut of 2 mm and a feedrate of 0.1 mm/revolution. Each test had the same total amount of removed material, with a spiral cutting length (SCL) of 727 m, divided into six or four passes depending on the alloy. Standard uncoated cemented carbide inserts (Sandvik CoromantTCMW16T304, grade Sandvik H13A equivalent to ISO S20) were used with 0.4 mm tip radius.

The above-mentioned superalloys can be found in a wide variety of states, obtained by thermal heating and cooling processes. Annealing is the one that we will consider in this study. The physical process of annealing produces microestructural changes that include recrystallization and grain growth [5]. The crystallization structure of alloys treated at high temperatures and for long annealing periods will break up and the subsequent recrystallization processes will differ, depending on the rapidity of the annealing or cooling process. Note that while grain growth can be provoked through heat treatment, the same is not true for the reduction of grain size. Recrystallization and grain growth processes can both be controlled by regulating the heating and the cooling times.

Two states of grain size *Large Grain* (LG) and *Small Grain* (SG) can be distinguished in Figure 1. In terms of strength, *Aged* (A) refers to a stronger state than and *Solutioned* (S).



Fig. 1. Structural differences at a microscopic level between LG and SG in different superalloys.

Turning processes require lubrication to reduce high temperatures and to extend the life of tools subjected to high torque forces during the machining process. Both [16] and [10] discussed lubrication in their studies. In this case, the selected parameters for temperature reduction were a *conventional lubrication system* at a pressure of 6 *bars* and a High Pressure Coolant (*HPC*) system at a pressure of 80 *bars*. In radial turning processes, a pass is considered finished when the tool has moved from the surface of the material to the final point on the axis. A pre-determined number of passes made sequentially are called a test. The number of passes needed to complete a full test differed in acccordance with the materials that were studied in this paper. 6

Table 1. Number of tests for each superalloy (Inconel, Haynes, Waspalloy), grain size, strength (SGS, SGA, LGS, LGA) and type of lubrication (Conventional, HPC).

		SGS	SGA	LGS	LGA
Inconel	Conventional	2	2	2	2
	НРС	-	3	-	2
Haynes	Conventional	-	-	2	2
	НРС	-	-	1	1
Waspalloy	Conventional	2	2	1	1
	НРС	1	1	1	1

passes were required to complete a test on *Inconel 718* and *Waspalloy*, while 4 passes were needed for *Haynes*. Table 1 shows the number of tests for each superalloy, the grain size, and the lubrication systems.

The initial conditions set up in this study were the same for every superalloy in every state.

While each pass was running, the cutting force of the tool in contact with the superalloy was measured. This force was then decomposed into three components, *Fx*, *Fy*, *Fz*, which were perpendicular to each other. Once a pass had finished, tool wear was also measured, in two different ways: *flank wear* and *notch wear*. *Flank wear* was measured at nine different points where the tool enters into contact with the superalloy. *Notch wear* appears just after *flank wear* and is usually larger. Note that only *flank wear* is studied in this paper. *Notch wear* was not studied, due to it having no relation with the force signals generated during the process that are a key focus of this study.

Figure 2 illustrates, the three force components. These signals are taken from one particular pass: in general, the signals from any of the passes will be of a similar appearance.

The main purpose of this paper is to predict tool wear under different settings. Given the direct relationship between tool wear and process stability, we study process instability in terms of the force signal; not only for the complete test but also for each pass. Then we create a linear mixed model to compare the wear for different setting situations and to predict the expected wear.

Note that an expert will be able to label each complete pass as either stable or unstable. Once a pass is labeled as unstable the whole test is considered unstable.



Fig. 2. Measured forces for a single pass for the three components.

## 4. Methodology

In this study, we have two goals: to identify the instability that can occur in irregular turning processes; and, to identify tool wear, the critical parameter during the turning process. The following sections explain the methodology to reach each goal.

# 4.1. Instability Detection

Instability has a direct relationship with tool wear linearity. An unstable process results in non-linear tool wear, causing a disturbance in the process.

First, we studied stability in each pass of every test, independently. Then, we analyzed the stability of the full test composed of several passes, comparing a given pass with the first pass, previously identified as stable or unstable.

### 4.1.1. Instability detection of a pass

Let the signals of the force components of a pass p be  $(F_{xt}(p), F_{yt}(p), F_{zt}(p))_t$ , recorded at a series of time-points t = 1, ..., T for passes p = 1, ..., 6. The instability of any one given pass, p, must be detected. The instability of a pass is closely related to the outlying data

values of the force components that were analyzed with the *three-sigma edit* rule [8].

This simple robust method allows us to obtain the median value of each force component,  $Me_c = Median_t \{F_{ct}(p)\}$ , and the corresponding absolute standard deviations, and can be expressed as:

$$|F_{ct}(p) - Me_c|, t = 1,...,T; c = x,y,z,$$

where, c is the axis of the force, t is the machined piece, and p is the pass.

The median value of these deviations is calculated and divided by 0.6745 as indicated in [8]:

$$MADN_{c}(p) = \frac{Median_{t}\left\{|F_{ct}(p) - Me_{c}\right\}}{0.6745}$$

The robust three-sigma edit rule (see [8]) establishes that observation  $F_{ct}(p)$  is an outlier, if:

$$|F_{ct}(p) - Me_c| > r,$$

where, r is a threshold value. Under the normality assumption, r = 3 is often set (hence the "three-sigma rule") and any observations beyond that threshold are considered outliers. Based on the three-sigma edit rule, a component force, c, at pass, p, is considered unstable, if:

$$Max_t(p) = \left\{ \frac{|F_{ct}(p) - Me_c|}{MADN_c(p)} \right\} > r.$$
(1)

In the case studied here, pass p is considered unstable if at least 2 of the 3 force components x, y or z are considered unstable. We explore different threshold values to establish the best one in this case. The goodness-of-fit is measured by the accuracy between the label given by the proposed approach (stable/unstable) and the expert's label. It is determined by a confusion matrix (Table 2), where the rows show the predicted values and the columns show the expert classification. Accuracy is given as a percentage value representing an approximation between the state predicted by the approach and expert classification.

Table 2. Confusion matrix in a classification problem

	Real class			
Pred. class	Stable	Unstable		
Stable	Тр	Fp		
Unstable	Fn	Tn		

$$Accuracy = \frac{Tp + Tn}{Tp + Tn + Fp + Fn}$$
(2)

The variability of the accuracy was measured by a moving blocks bootstrap approach [18]. This statistical technique is used to obtain bootstrap samples from correlated data. The signal is divided into contiguous blocks of length L. Following sampling with replacement from the blocks, the signals were then processed with a bootstrap technique. In this process, the threshold providing the highest accuracy is considered as the optimum value to detect the instability of a pass.

In this study, the above approach is only applied to the first pass of each test, due to the importance of this pass in the stability of the whole test.

### 4.1.2. Instability detection of a whole test

In this section, an instability-detection method is used to analyze the stability of the whole test. The approach is based on the comparison of any given pass of the test with the corresponding first pass of the test. First, the classical statistical technique of Principal Component Analysis (PCA) [3] is applied to reduce the dimension from the 3 force components to only two dimensions, so that the full signal of forces of the first pass can be easily visualized. PCA is based on combining linearly input features, in this case the force components of the first pass ( $F_{ct}(1)$ , t = 1, ..., T; c = x, y, z), to obtain new ones  $(C_{k}(1), k = 1, 2)$  that are linearly independent between each other and maintain as much of the original information as possible. Second, subsequent passes are projected on the same space, so the progress of the test can be seen graphically. In addition to graphical classification, a quantitative measure is calculated: given  $F_t(p) = (F_{xt}(p), F_{vt}(p), F_{zt}(p)),$ the maximum distance from any time point, t, of this pass, p, to the centroid of the first pass is as follows:

$$D(p) = \max_{t} \left\{ \sqrt{\sum_{c} \left( F_{c,t}(p) - \overline{F_{c}(1)} \right)^{2}} \right\}$$

These distances are obtained for each test and are used to determine the stability of the test; as a result, the test will be classified as unstable when the value D(p) is twice the value of D(1) in the first pass.

Validation of this model is done by comparing the stability classification that is obtained with the one offered by the expert. To do so, the confusion matrix is calculated and an accuracy value is obtained.

### 4.2. Tool-wear prediction

In this section, the objective is to model the radial turning according to some of the variables sensorized during the process and some others that depend on the material. Throughout the turning process for each piece, the wear at the end of each pass is recorded. The effect of each pass is the most important variable to take into account to build a model for the evolution of the wear. Nevertheless, factors that include the type of alloy, grain size, lubrication pressure, as well as forces on each component are considered. Since the wear is measured several times on the same piece or tool along the turning process, these measurements may be correlated. A linear mixed-effect model (LMM), capable of properly processing the data correlations, generated the model of tool wear.

A brief explanation would be that the dependent variable  $\mathbf{w} = (w_{ip})_{ip}$  (in this study the wear, where  $w_{ip}$  stands for the tool wear, *i*, at the end of a pass, *p*) is formulated within the following general model in an LMM:

$$\mathbf{w} = \mathbf{X}\beta + \mathbf{Z}\mathbf{b} + \epsilon$$
,  $\mathbf{b} \sim N(\mathbf{0}, \mathbf{D})$  and  $\epsilon \sim N(\mathbf{0}, \mathcal{R})$ ,

where **X** is a  $n \times k$  matrix (k is the number of fixed effects), **Z** is a  $n \times q$  matrix (q is the number of random effects) and D is the variancecovariance matrix ( $q \times q$ ) of the random effects. The random effects (which are modeled by random variables) in these models permit the prediction of the behavior of particular units in the sample, as well as an estimation of variability between different units.

Inference for the model selection was performed with the Likelihood Ratio (LR) test for the fixed effects and by chi-squared distributions derived from Restricted Maximum-Likelihood Estimation-based LR tests for variances and covariances of the random effects (see [2] for details). The diagnosis of the model was not done by the analysis of the residuals. Instead, the Normalized Root Mean Square Deviation (NRMSD) statistic was used, to give a quantitative value of the approximation, where lower values indicate less residual variance.

## 5. Results

The results are organized into two main sections. In the first one, the results on instability detection are shown and, in the second, those concerning tool wear.

## 5.1. Instability Detection

As a first step, we studied the time series signal of each first pass considering different threshold values in equation (1). As mentioned in section 4.1.1, a threshold value has been searched for, in order to determine the optimum value for this specific process. The stable/unstable label obtained was compared with an expert opinion and the accuracy value was calculated. The standard deviation of the accuracy was measured on 200 bootstrap samples (see Table 3).

Threshold	Accuracy(std)
3	0.28 (0.000)
5	0.28 (0.032)
7	0.72 (0.047)
8	0.82 (0.039)
9	0.79 (0.017)
10	0.79 (0.018)

Table 3. Accuracy value and its bootstrap estimated standard deviation (std) for different thresholds

The results showed that the best threshold value was r = 8. Moreover the approach was not dramatically sensitive to the threshold value and values above r = 8 also yielded comparable results.

As a second step, the stability of the test based on the first pass was studied. The technique of Principal Component Analysis (PCA) produced a global summary of the forces in graphic form. Two PCA analyses can be seen in Figures 3 and 4, which present all the passes of a test for stable and unstable tests, respectively. A test is considered unstable when a particular value D(p) of any pass, p, is over twice the maximum distance of the first pass, D(1).

The maximum distance from the first pass centroid to any of the points of each pass is shown for both stable (Figure 5a) and unstable tests (Figure 5b). These values were obtained for the rest of the tests and the results following their comparison with the expert stability classification are shown in Table 4.

In Table 4, it can be seen that most of the tests are well classified, which accounts for 76% of the accuracy, calculated as the percentage of well classified values divided by the sum of all values (see equation. 2).

	Expert's classification			
Pred. class.	Stable	Instable		
Stable	13	5		
Instable	2	9		

Table 4. Confusion matrix comparing the classification given by the expert (columns) and the obtained (rows) by comparing the maximum distances from the centroid of the first pass to the others: D(p).

#### 5.2. Tool-wear prediction

During the radial turning process, each tool, *i*, is related with its experimental setup conditions (i = 1,...,29). Particularly, the type of superalloy and the lubrication system were of significant importance for tool wear throughout the model selection process, although the same could not be said for grain size, strength, and the forces that the



Fig. 3. Principal Component Analysis of a stable test, composed by 6 stable passes

tool withstands. Taking all these issues into account, the fitted model is as follows:

$$\begin{split} & w_{ip} = \beta_0 + \beta_1 \text{Haynes}_i + \beta_2 \text{Waspalloy}_i + \beta_3 \text{Conventional}_i + b_{0i} \\ & + (\beta_4 + \beta_5 \text{Haynes}_i + \beta_6 \text{Waspalloy}_i + \beta_7 \text{Conventional}_i)p + b1ip \\ & + \epsilon_{ip} \end{split}$$

where:

- $w_{ip}$  is the wear of the *i*th tool at the end of the pass *p*,
- Haynes<sub>i</sub> and Waspalloy<sub>i</sub> are dummy variables that indicate the type of superalloy that the *i*th tool is cutting, and Conventional<sub>i</sub> is the dummy variable for the lubrication system of the *i*th tool,
- the random effects of the model are:

$$\binom{b_{0i}}{b_{1i}} \sim N(0,\mathcal{D}) \quad with \binom{d_{11}}{0} \binom{d_{12}}{d_{22}},$$

• the errors of the model have 0 mean but are heterocedastical

$$VAR(\epsilon_{ip}) = \sigma^2 \theta_i^2$$

with  $\theta_i^2 = 1$  if the *i*th tool is stable and  $\theta_i^2 = 1$  otherwise.

The estimations of the parameters of the model and 95% approximate confidence intervals are in Table 5 as well as the *p*-values for the fixed effects. The latter are obtained by Maximum Likelihood.

It is noteworthy that the variability between tools is much bigger than the residual variability, even for stable tests. For instance, by the intraclass correlation, 77% of the variability of the slope at each pass, *p*, is due to the variability between tools. Nevertheless, some general main effects can be assumed: each pass, *p*, on an *Inconel 718* alloy with HPC lubrication provokes mean tool wear of 19.4 mic. If the alloy is *Haynes* or *Waspalloy*, there will be less wear after each pass: mean average wear of 11.2 mic and 16.7 mic less, respectively. For a given alloy, when a conventional lubrication system was used, a higher mean wear of 13.2 mic compared with the HPC lubrication system was noted.

Using the model obtained and taking into account the maximum permitted tool wear (300 mic), it was easy to see that the tool could work properly with many more passes (a range from 10 to 81 passes depending on the tools). The prediction tendency for each of the



Fig. 4. Principal Component Analysis of an unstable test. The same axis in each of the 6 passes is shown, to highlight the variability of this process



Fig. 5. Maximum distance to the centroid of the first pass D(1) for each pass D(p)

tests is shown in Figure 6. The Normalized Root Mean Square The deviation measure (NRMSD) for the stable tests was 13.3%, which means that the mean percentage error for measured wear using LMM was 13.3%.

# 6. Conclusions

Two problems with a wide variety of industrial consequences for machining work have been discussed in this paper.

	Parameter	Estimation	<i>p</i> -value
Fixed effects	$\beta_0$	83.1 (71.4, 94.8)	<.0001
Superalloy	$\beta_1$ (Haynes)	9.7 (-5.5, 25.0)	0.0032
	$\beta_2$ (Waspalloy)	-10.6 (-24.7, 3.6)	
Lubrication	$\beta_3$ (conventional)	-18.7 (-30.5, -6.9)	0.0213
Pass p	$eta_4$	19.4 (12.9, 25.9)	<.0001
Superalloy×Pass	$\beta_4$ (Haynes ×p)	-11.2 (-19.9, -2.6)	<.0001
	$\beta_4$ (Waspalloy ×p)	-16.7 (-24.0, -9.4)	
Lubrication ×Pass	$\beta_7$ (conventional ×p)	13.1 (6.5, 19.7)	0.0001
Random effects SD(b <sub>0i</sub> )	$\sqrt{d_{11}} \sqrt{d_{22}}$	10.9 (6.4, 18.5)	
$SD(b_{1i})$		8.5 (6.3, 11.4)	
Errors	σ	4.6 (3.7, 5.7)	
	$ heta_i$	5.4 (4.2, 7.1)	





Fig. 6. Prediction of the tool wear for each test as a function of the material and the lubrication system.

One aspect of this study is the development of a method for instability detection that can detect initial instability in radial turning processes. The three components of the measured force have been selected as the most important variables. These variables have been applied to two different methods with two goals; an off-line method, MADN, was used for first pass stability, which can be extended to the rest of the passes, and which produced an accuracy of 82% of the signals. Another methodology was based on PCA visualization, which provided an intuitive 2 dimensional representation of the forces. Applied on-line, it can function as a fault-detection method during machining processes and will, if necessary, end the process. The results applied to all the tests achieved an accuracy rate of 76%.

This result offers a better process-oriented view to the operator that is easier to understand. The algorithms can be directly integrated into the on-line monitoring tool, to analyze the effect of using a particular tool and material. The general approach in this work can be used in an experimental phase to improve the process with new materials.

A further aspect is that a tool-wear model based on a Linear Mixed Model has been applied. The model has shown that mean average tool wear differs, depending on the type of superalloy and lubrication system in use, as suggested in [16] and [10]. It is worth mentioning that the force of the tool in contact with the superalloy is not an important input variable in the model. The model has also been used to demonstrate that the tool can withstand a higher number of passes, with tool wear under 300 mic. while the stability of the turning process is held. As a consequence, the process could run longer without stopping, which would imply faster turning and less time to finish the piece. Finally, a confirmatory analysis using a larger amount of samples would be of interest, to reduce the uncertainty and variability of the different pieces.

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# References

- 1. Galar D, Palo M, Van Horenbeek A, and Pintelon L. Integration of disparate data sources to perform maintenance prognosis and optimal decision making. Insight-non-destructive testing and condition monitoring 2012; 54 (8): 440-445, https://doi.org/10.1784/insi.2012.54.8.440.
- 2. Galecki A, and Burzykowski T. Linear mixed-effects models using R: A step-by-step approach. Springer Science & Business Media, 2013.
- 3. Jolliffe I T, and Cadima J. Principal component analysis: a review and recent developments. Phil. Trans. R. Soc. 2016; 374, 2065, 20150202.
- Kebdani S, Sahli A, Rahmani O, Boutchicha D, and Belarbi A. Analysis of chatter stability in facing. Journal of Applied Sciences 2008; 8 (11): 2050-2058, https://doi.org/10.3923/jas.2008.2050.2058.
- Lee Y B, Shin D H, Park K-T, and Nam W J. Effect of annealing temperature on microstructures and mechanical properties of a 5083 al alloy deformed at cryogenic temperature. Scripta materialia 2004; 51 (4): 355-359, https://doi.org/10.1016/j.scriptamat.2004.02.037.
- Liu Q, and Altintas Y. On-line monitoring of flank wear in turning with multilayered feed-forward neural network. International Journal of Machine Tools and Manufacture 1999; 39 (12): 1945-1959, https://doi.org/10.1016/S0890-6955(99)00020-6.
- Mahamad A K, Saon S, and Hiyama T. Predicting remaining useful life of rotating machinery based artificial neural network. Computers & Mathematics with Applications 2010; 60 (4): 1078-1087, https://doi.org/10.1016/j.camwa.2010.03.065.
- 8. Maronna R, Martin R D, and Yohai V. Robust statistics. John Wiley & Sons 2006; Chichester.
- 9. Maruda R W, Krolczyk G M, Feldshtein E, Nieslony P, Tyliszczak B, and Pusavec F. Tool wear characterizations in finish turning of aisi 1045 carbon steel for mqcl conditions. Wear 2017; 372: 54-67, https://doi.org/10.1016/j.wear.2016.12.006.
- Maruda R W, Krolczyk G M, Nieslony P, Wojciechowski S, Michalski M, and Legutko S. The influence of the cooling conditions on the cutting tool wear and the chip formation mechanism. Journal of Manufacturing Processes 2016; (24): 107-115, https://doi.org/10.1016/j. jmapro.2016.08.006.
- 11. Ozel T, Karpat Y, Figueira L, and Davim J P. Modelling of surface finish and tool flank wear in turning of aisi d2 steel with ceramic wiper inserts. Journal of materials processing technology 2007; 189 (1-3): 192-198, https://doi.org/10.1016/j.jmatprotec.2007.01.021
- 12. Rao C S, and Srikant R. Tool wear monitoringan intelligent approach. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2004; 218 (8): 905-912, https://doi.org/10.1243/0954405041486028.
- 13. Repo J. Condition monitoring of machine tools and machining processes using internal sensor signals. PhD thesis, KTH Royal Institute of Technology, 2010.
- Sekar M, Srinivas J, Kotaiah K R, and Yang S-H. Stability analysis of turning process with tailstock-supported workpiece. The International Journal of Advanced Manufacturing Technology 2009; 43 (9-10): 862-871, https://doi.org/10.1007/s00170-008-1764-2.
- 15. Shaban Y, and Yacout S. Predicting the remaining useful life of a cutting tool during turning titanium metal matrix composites. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2016; 0954405416654184.
- 16. Suarez A, Lopez de Lacalle L, Polvorosa R, Veiga F, and Wretland A. Effects of high-pressure cooling on the wear patterns on turning inserts used on alloy in718. Materials and Manufacturing Processes 2016; (1-9).
- 17. Tangjitsitcharoen S. In-process monitoring and detection of chip formation and chatter for cnc turning. Journal of Materials Processing Technology 2009; 209 (10): 4682-4688, https://doi.org/10.1016/j.jmatprotec.2008.10.054.
- 18. Tibshirani R J, and Efron B. An introduction to the bootstrap. Monographs on Statistics and Applied Probability 1993; (57): 1-436.
- Wu D, Jennings C, Terpenny J, Gao R, and Kumara S. Data-driven prognostics using random forests: Prediction of tool wear. In ASME 2017 12th International Manufacturing Science and Engineering Conference collocated with the JSME/ASME 2017 6th International Conference on Materials and Processing 2017; American Society of Mechanical Engineers; V003T04A048-V003T04A048.
- 20. Xue H, Wang S, Yi L, Zhu R, Cai B, and Sun S. Tool life prediction based on particle swarm optimization-back-propagation neural network. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2015; 229 (10): 1742-1752, https://doi. org/10.1177/0954405414538961.

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# ANALYSIS OF THE EXPLOITATION FAILURE RATE IN POLISH MV NETWORKS

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The paper presents an analysis of exploitation failure rate in MV overhead and cable lines and in MV/LV transformers in the Polish power system. The reliability analysis is carried out by means of a non-parametric method using kernel estimators. The data are obtained from power networks of various operating conditions, and because of that the weight of data is taken into consideration. Additionally, the paper offers an innovative way of presenting the reliability data in a graphic form.

Keywords: reliability, failure rate in MV networks, kernel estimators.

W artykule przedstawiono wyniki analizy danych eksploatacyjnych awaryjności linii napowietrznych i kablowych średniego napięcia jak również transformatorów SN/nN krajowego systemu elektroenergetycznego. Do analizy zagadnienia zastosowano nieparametryczną metodę analizy danych niezawodnościowych sieci elektroenergetycznych z wykorzystaniem estymatorów jądrowych. Poszczególne dane pochodzą z sieci elektroenergetycznych mających różny charakter pracy, dlatego uwzględniono w analizie wagę poszczególnych danych. W artykule zaproponowano także nowy sposób prezentacji graficznej analizowanych danych niezawodnościowych.

Słowa kluczowe: niezawodność, awaryjność sieci średniego napięcia, estymatory jądrowe.

# 1. Introduction

The issues related to the reliability of power systems are currently in the centre of interest all over the world. Unconstrained and continuous access to electricity is generally taken for granted, and people are becoming increasingly dependent on it. What a consumer expects is both the correct operation of electrical appliances, i.e. high-quality energy [14]) and uninterrupted access, i.e. reliable supply of energy [14]. Consumers expectations can be unfulfilled due to the technical condition of the distribution network, which motivates research on methods of assessing the reliability of energy supply systems.

It is possible to analyse the power system reliability in many respects. A great number of empirical and theoretical studies have been devoted to this topic, beginning with the works of Roy Billinton and Ronald N. Allan, who jointly [2] and together with a team of co-researchers published extensively on the topic. Polish researchers have also published a number of works, of which those by Józef Paska [13, 14] or Andrzej Chojnacki [5] are the most widely known.

Reliability analysis can be applied to the production, transmission or distribution of electric energy. The reliability of the distribution system concerns the three voltage levels, i.e. high, medium and low voltage, with separate reliability parameters determined for each of them, as well as the system of connections and functional dependences between the three levels [1-10, 13, 14, 16]. Real power network systems are often quite extensive, and their reliability is typically assessed by means of commonly applied indices such as SAIDI, SAIFI or MAIFI [1, 2, 9, 10]. The indices are calculated on the basis of events registered in a network operated by a distribution company. Besides, distribution companies use information on the reliability of particular groups of power devices. It has to be noted that it is difficult to collect extensive reliability data for the sake of research. The data collected by distribution companies are treated as confidential and are not available to the public, they only get published in a fragmentary or generalized form [19]. An exception to this rule and an example of good practice is the report [1], presenting analyses of the reliability of European power systems. The publication of such reports increases availability of information and enhances transparency of reliability and energy quality policies applied in each of the countries included in the report.

Besides, a correct assessment of reliability is crucial for a distribution company to develop a strategy of exploitation and investment in the network so that the reliability targets imposed by the Energy Regulatory Office (ERO) can be met. It is very important for companies, which are obliged to report their reliability indices to ERO and if real reliability indices turn out not to meet the yearly targets, a company can be fined.

It has to be noted too, that the reliability data are collected from power networks of different operation characteristics, covering different areas and serving different numbers of customers. It is therefore necessary to take into consideration the weight of particular data in the analysis. Besides, it should also be emphasized that the classical statistical methods typically employed in the analysis of reliability data, such as Weibull, exponential or log-normal distributions, may be inadequate. These methods, referred to as parametric, rely on arbitrarily adopted typical distribution of random variables, on the basis of which parameters of the assumed distribution are subsequently obtained [5]. The reason why they are insufficient for analysing reliability problems is that the number of possible distributions is limited [12]. Non-parametric methods are free from this limitation, since no function is assumed a priori [11, 12].

It can be observed on the basis of statistical analysis of failures in power networks that the majority of breakdown occur in MV and LV lines [7-10]. The most frequent causes of failures are of random nature and include atmospheric overvoltage, SEMP, sudden changes in ambient temperature, wind, hard rime, effects of air pollution or human factors [5]. The data on failures in power networks should be reported

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in statistical sheets G-10.5, filled in by distribution companies. The sheet includes the values of indices characterizing the failures of elements in the MV and LV power networks.

This paper offers an analysis of data obtained from the sheets G-10.5 submitted by 19 distribution companies in the years 2012 - 2014. The distributions of the density functions of the reliability indices were calculated by means of nonparametric methods, which represent the variation of the phenomena under investigation in a credible way [11, 12]. Kernel estimators presented in further parts of the paper are precise in mathematical terms and are universally applicable. Combined with computational capacity of computers, kernel estimators can be successfully used in analyses of highly complex problems.

The main objective of the paper is to present an estimation of the function of the random variable distribution density on the basis of a sample. All the statistical computations have been carried out in the programming environment of the language R [15]. For each analysis of reliability data a program has been developed for calculating reliability of a group of devices under scrutiny and graphs supporting the process of statistical inferencing have been plotted.

### 2. Numerical data analysis

One of the fundamental problems that has to be solved in analyses of complex technological processes is obtaining functions characterizing an object under scrutiny on the basis of experimental data available. The reliability analysis of individual devices and of the whole power system requires determining adequate statistical measures on the basis of historical data. The typical cases of this problem include obtaining the mean value, the standard deviation, the regression function, or the estimation of the probability density function (pdf) for a random variable. When estimating the pdf, the type of the random variable distribution is usually arbitrarily assumed and its parameters are subsequently determined. Because of that, these methods are referred to as parametric.

### 2.1.1 Kernel estimators

As far as non-parametric estimation methods are concerned, the one based on kernel estimators is among the most widely applied. Non-parametric methods were put forward at the turn of the 1950s and 60s and their basic idea is derived from the pdf estimation problem, as discussed in a number of publications, e.g. [11, 12, 21-23].

A typical problem to which kernel estimators can be applied is obtaining the density function of the probabilistic distribution of the random variable on the basis of a sample (i.e. Kernel Density Estimation – KDE). To implement kernel estimators for analysing random variables, it is necessary to have access to a computer with software for statistical analyses, such as the program R.

### Definition of a classical kernel estimator - KDE.

Let X be an *n*-dimensional random variable, with the distribution density f. Its kernel estimator  $\hat{f} : \mathbb{R}^n \to [0,\infty)$  is determined on the basis of an *m* element random sample  $x_1, x_2, \dots, x_m$ , obtained from the variable X. The basic form of the kernel is defined by the

$$\hat{f}(x) = \frac{1}{mh^n} \sum_{i=1}^m K\left(\frac{x - x_i}{h}\right) \tag{1}$$

where the function called a kernel,  $K : \mathbb{R}^n \to [0,\infty)$  which is measurable, symmetrical with respect to zero and having a weak global max-

imum at this point, satisfies the condition  $\int_{\mathbb{R}^n} K(x) dx = 1$ . The posi-

tive coefficient h is known as bandwidth [11, 20-23].

From the statistical point of view, the form of the kernel is not significant. It is possible to choose the kernel form on an arbitrary basis. Due to the fact that many natural phenomena, including those affecting reliability data, are subject to normal distribution, it appears justified to apply the normal kernel as defined by the function:

$$K(x) = \frac{1}{\sqrt{2\pi}} e^{\left(\frac{-x^2}{2}\right)}$$
(2)

The normal kernel has a disadvantage though, namely the unlimited carrier of the random variable  $x \in (-\infty, \infty)$ . since the estimated values of the reliability parameters can be only positive, the form of the kernel estimator has to be modified in such a way that the random variable X can take only non-negative values. This can be done by stipulating a constraint on the kernel carrier, the role of which is to mirror the part of kernel located beyond the permitted interval, i.e. in the case of reliability random variables, it is those below zero [11, 21, 23].

Another modification of the classical KDE involves introducing weights. In this way, a weighted kernel density estimator (KDEw) is obtained.

### Definition of a weighted kernel density estimator KDEw.

Let X be an *n*-dimensional random variable, with the distribution density f. Its kernel estimator  $\hat{f} : \mathbb{R}^n \to [0,\infty)$  is obtained on the basis of an *m*-element random sample  $x_1, x_2, \dots, x_m$ , to which non-negative values  $w_1, w_2, \dots, w_m$  are attributed. The values satisfy the condition  $\sum_{i=1}^m w_i = 1$  and are further referred to as weights of the

particular elements of the variable X, as defined by the formula:

$$\hat{f}(\mathbf{x}) = \frac{1}{h^n \sum_{i=1}^m w_i} \sum_{i=1}^m w_i K\left(\frac{\mathbf{x} - \mathbf{x}_i}{h}\right)$$
(3)

where the function  $K : \mathbb{R}^n \to [0,\infty)$  is the kernel. It is measurable, symmetrical with respect to zero, has a weak global maximum at this point and satisfies the condition  $\int_{\mathbb{R}^n} K(x) dx = 1$ . The positive coeffi-

cient h is the bandwidth, as described in [11, 23].

In the special case when all the weights  $w_1, w_2, ..., w_m$  are equal and their sum is 1, the form of the estimator KDEw specified in (3) becomes equivalent to that in (1), i.e. the KDE.

In this paper I shall argue that the use of KDEw provides a more adequate model for the analysis of the reliability of a power system than KDE. The results of such an analysis should be however approached with caution if the weights take extremely disparate values. In such a case, before accepting the outcome of the statistical calculations, it is necessary to verify them on the basis of theoretical and practical familiarity with the phenomena under scrutiny to avoid drawing erroneous conclusions.

The quality of kernel estimators is crucially affected by the bandwidth h, which ensures the smoothness of the density function. If the parameter value is too small, there are too many local extremes of the estimator  $\hat{f}(x)$ , if its value is too high, the function  $\hat{f}(x)$ is excessively smoothed and ceases to represent the real properties

formula:

of the random variable. A number of useful algorithms are offered in the literature for calculating the value of the parameter h, optimized on the basis of a Mean Squared Error criterion. Methods for optimizing the estimation of the parameter h are also implemented in the popular statistical analysis software, such as SAS, R, MATLAB or STATYSTYKA.

In the R program environment [15], there are a number of functions available for calculating a pdf of a random variable by means of kernel estimators. In this study, the function 'density' was used, which comes in a number of calculation options. One of them includes the parameter 'weights', defining the weights for the particular values of a random variable. The method of obtaining the parameter h selected by means of the parameter 'bw'. The method employed here for obtaining the value of the bandwidth h has the Sheather & Jones method. It is worth mentioning that the function 'density' and the software R were exploited in my previous studies too [7-10].

When the data are multidimensional, two natural generalization of the above-mentioned formulas are employed: a radial kernel [11, 23]:

$$K(x) = C K\left(\sqrt{x^T x}\right) \tag{4}$$

and product kernel:

$$K(x) = K\left(\left[x_1, x_2, \dots, x_n\right]^2\right) = K(x_1) \cdot K(x_2) \cdot \dots \cdot K(x_n) \quad (5)$$

where K is a one-dimensional kernel, and C is a positive constant of such a value that the condition  $\int_{\mathbb{R}^n} K(x) dx = 1$  s satisfied. Radial ker-

nel is more effective than product kernel, but from the perspective of applications, the difference is insignificant, as pointed out in publications [11, 23].

### 3. Analysis of exploitation failures in MV networks

The failure analysis of MV networks presented in this study was carried out on the basis of data obtained from 19 Polish distribution companies, covering 57 % of the area of Poland, supplying about 65 % of total energy consumption to over 10.5 million consumers (as of the end of 2015). The total length of the power lines used for energy transmission is over 465 thousand km. It can be assumed that this is a statistically significant sample for carrying out reliability analysis concerning Polish power networks.

Each Polish distribution company is obliged to submit a statistical report on the condition of electrical devices, known as G-10.5. This report includes the company's confidential data on the network condition and the functioning of particular power devices in the preceding calendar year. The report is submitted to Agencja Rynku Energii Spółka Akcyjna (ARE S.A.) for the sake of conducting statistical analysis and systematic research on power industry. ARE S.A. processes the data jointly but the results are confidential and are therefore not made available to the public. In a comprehensive report called "Statystyka Energetyki Polskiej" [19], only mean values of indices obtained for the whole Polish power industry are published. It is not possible to obtain data on the power system reliability for particular distribution companies.

In the G10.5 report, the failure rate in MV power networks is described in terms of:

- the number of failures in MV overhead and cable lines and in MV/LV transformers;
- a failure index per 100 km of overhead and cable lines, respectively, and per 100 MV/LV transformers;
- average interruption time expressed in hours in electricity supply caused by failures in MV cable and overhead lines and in MV/LV transformers.

The total number of failures registered in the MV network devices in the period 2012 - 2014 was 53 089. A summary of failures occurring in various types of devices in MV networks is presented in Table 1.

In 2014 the distribution companies taken into account in the present analysis jointly served 128 655 km of overhead MV lines, 39 165 km of MV cable lines and 146 627 MV/LV transformers.

Table 2 presents the length of MV cable lines SN  $(l_{SN\_LK})$ , the length of MV overhead lines  $(l_{SN\_LN})$  and the number of MV/LV transformers  $(l_{Tr})$  (each distribution company, together with weights attributed to them (waga)The value of the variable waga obtained from the following formula:

$$waga_i = \frac{x_i}{\sum_{i=1}^{19} x_i} \tag{6}$$

where  $x_i$  is the value corresponding to the length of lines or the number of transformers in a company divided by the sum obtained for all the 19 companies.

The calculated values of the variable *waga* are used for determining KDEw, discussed below.

Below a statistical analysis will be carried out of the data with respect to failure indices (w) and with respect to mean interruption duration due to failure (t) for three groups of devices: MV cable lines, MV overhead lines and MV/LV transformers.

In each of the groups the data set included 57 observations (i.e. 3 values from the period 2012–2014 in the 19 distribution companies).

The results obtained are presented at three types of graphs: a histogram, a boxplot and a pdf. The pdf is obtained by means of kernel estimators with a normal kernel, the carrier being constrained to positive values. The bandwidth coefficient h as obtained by means of the most widely accepted method developed by Sheather & Jones [17].

The calculations of the pdf by means of kernel estimators were carried out in two variants – the classic KDE variant without weights and the KDEw variant in which the significance of data is weighed. In non-weighed KDE each datum has the same significance in the analysis, whereas in the weighed variant the data with greater weights have greater significance in the calculations. The variables that are

Table 1. Number of failures registered in the MV network that occurred in overhead lines, cable lines and MV/LV transformers in the period 2012 – 2014

Numb	[%]		
Total number of failures in:	MV overhead lines	38 869	73.21
	MV cable lines	11 865	22.35
	MV/LV transformers	2 355	4.44
	53 089	100.00	

	MV overl	nead lines	MV cab	le lines	MV/LV tra	MV/LV transformers	
Company code	l <sub>SN_LK</sub> [km]	waga <sub>SNLK</sub>	[m]	waga <sub>SN_LN</sub>	l <sub>Tr</sub> [Units]	waga <sub>Tr</sub>	
А	2 302	0.0588	16487	0.1281	14606	0.0996	
В	2 926	0.0747	9687	0.0753	9810	0.0669	
С	2 367	0.0604	1509	0.0117	3631	0.0248	
D	1 700	0.0434	12715	0.0988	11744	0.0801	
Е	2 457	0.0627	11426	0.0888	11366	0.0775	
F	2 305	0.0589	13080	0.1017	13038	0.0889	
G	2 437	0.0622	14952	0.1162	17870	0.1219	
Н	1 074	0.0274	11416	0.0887	8916	0.0608	
I	2 368	0.0605	1873	0.0146	3640	0.0248	
J	1 384	0.0353	3233	0.0251	4630	0.0316	
К	1 291	0.0330	3926	0.0305	4017	0.0274	
L	5 036	0.1286	3011	0.0234	9350	0.0638	
М	717	0.0184	2823	0.0219	2759	0.0188	
N	3 341	0.0853	3441	0.0267	9938	0.0678	
0	914	0.0233	2933	0.0228	2785	0.0190	
Р	1 815	0.0463	5080	0.0395	5189	0.0354	
R	731	0.0187	3979	0.0309	4050	0.0276	
S	901	0.0230	2982	0.0232	3190	0.0218	
Т	3 099	0.0791	4102	0.0319	6098	0.0416	
Total	39 165	1.0000	128 655	1.0000	146 627	1.0000	

Table 2. Length of MV cable lines SN ( $l_{SN\_LK}$ ), length of MV overhead lines ( $l_{SN\_LN}$ ), number of MV/LV transformers ( $l_{Tr}$ ) in each distribution company marked by a code A-T and weights attributed to the data



Fig. 1. Histogram, boxplot and a pdf obtained by means of KDE (continuous line) and KDEw with the weight  $waga_{SN\_LK}$  (interrupted line) for the failure index  $w_{SN\_LK}$  and for the interruption duration  $t_{SN\_LK}$  in MV cable lines

used as weights in further calculations are the length of MV overhead lines, the length of MV cable lines and the number of MV/LV transformers. In the cases under scrutiny, the weights were of similar values, i.e. the greatest differences can be of one order of magnitude. This indicates that the weighed features in the power networks are in fact comparable.

The three types of graphs represent the same information in different ways. The most popular form is a histogram representing the data distribution in a basic visual way. The boxplot represents a graphic interpretation of the distribution of the statistical features of a variable. It provides information on the median, the 1st quartile (1 Qu)  $Q_1$  the 3rd quartile (3 Qu)  $Q_3$ , IQR (interquartiles) as well as outliers, exceeding 1,5 IQR, marked by circles. The KDE graphs are plotted by means of a continuous line and the KDEw graphs by means of

an interrupted line, representing modal values directly visible at the pdf curve, skewness, outliers and multimodality, if it occurs.

Besides, the plots offer additional graphical information on the value and weight of the particular data  $d_i$ . Along the base of the scale on the y-axis there are markers "|", located at places corresponding to the values of the data  $d_i$ . The height of these markers corresponds to the weight of data: the higher the marker "|", the greater the weight of a datum and the greater its contribution to the KDEw.

The descriptions attached to some figures include tables with selected statistical measures of the distributions, concerning the minimal and maximal values,  $Q_1$ ,  $Q_3$ , the median and the mean value of the variables.

Figures 1 and 2 present the failure analysis of MV cable lines.

The left-hand side graph in Fig. 1 depicts the pdf vs. failure index  $w_{SN\_LK}$  plot (bandwidth h = 1.578), whereas the right-hand side graph represents the pdf vs. the interruption time  $t_{SN\_LK}$ (h = 0.2652) in MV cable lines.

Additionally, a two-dimensional estimation of the pdf was carried out for the two variables under analysis, i.e. the failure index and the interruption duration in MV cable lines, using the function kde2d from the library MASS of the program R. The calculations were performed with the use of a normal kernel, constraining the carrier to



Fig. 3. Histogram, boxplot and a pdf obtained by means of KDE (continuous line) and KDEw with the weight  $waga_{SN\_LN}$  interrupted line) for the failure index  $w_{SN\_LN}$  and for the interruption duration  $t_{SN\_LN}$  in MV overhead lines



Fig. 2. Two-dimensional pdf obtained by means of KDE for the failure index  $w_{SN\_LK}$  and the failure duration  $t_{SN\_LK}$  in MV cable lines

the positive values, and obtaining the h by means of the Sheather & Jones method. The two-dimensional graph does not take weights into account (the KDE method). Using weights would not have a significant impact on the distribution, except their values at selected points. The two-dimensional pdf representing the failure rate and duration in MV cable lines is presented in Fig. 2.

In the cable networks of the distribution companies under study there were typically about 7 failures per 100 km of cable lines, lasting on average about 1.7 hours per year. Some of the distribution companies however had a higher failure rate in cable lines than others. These companies can be easily identified on the basis of the analysis, for example for the sake of conducting benchmarking research or planning investment.

Figures 3 and 4 present the failure analyses of the MV overhead lines. The failure index  $w_{SN\_LN}$  as obtained at the bandwidth h = 1.115, and its value for the interruption duration  $t_{SN\_LN}$  MV overhead lines was 0.2402. The pdf plots for the failure index  $w_{SN\_LN}$  calculated by means of KDE and KDEw differ only slightly and it can be stated that in the companies exploiting MV overhead lines of greater total length the values of  $w_{SN\_LN}$  were lower.

Fig. 4 presents a two-dimensional pdf representing the failure rate and duration in MV overhead lines.



Fig. 4. Two-dimensional pdf obtained by means of KDE for the failure index  $w_{SN\_LN}$  and the failure duration  $t_{SN\_LN}$  in MV overhead lines

Failure rates in MV overhead lines differs significantly among the companies under study. The modal value is about 8 failures per 100 km of lines with the duration of about 3.5 hours per year. A few companies however diverged from the others with respect to the failure rate, with company T experiencing almost 30 failures per 100 km lines in 2012, and with companies P and K in 2012, and company H in 2013–2014 having the interruption duration over 6 h.

Transformers are commonly believed to be highly reliable elements of the power system. Figures 5 and 6 present exploitation reliability analysis for MV/LV transformers. The left-hand side graph in Fig. 5 represents the failure index for MV/LV transformers (bandwidth h = 0.0924), whereas the righthand side graph depicts interruption duration h = 0.8714). Despite high differences in the number of transformers among the distribution companies (minimal/maximal share - 1.8%/12.2%) the KDE and KDEw plots are similar. This indicates that the failure rates of MV/LV transformers in particular distribution companies are similar. Only one significant value visible in the plot is an outlier in the distribution of interruption duration (company P in 2013).

The two-dimensional pdf for the MV/LV transformer failure rate presented in Fig. 6 confirms that the population under scrutiny is largely homogeneous.



Fig. 6. Two-dimensional pdf obtained by means of KDE for the failure index  $w_{Tr SN/nN}$  and for the interruption duration  $t_{Tr SN/nN}$  in MV/LV transformers



The plots depicting the failure rate of MV/LV transformers (Figures 5 and 6) indicate that the median of the distribution examined is 5.65 h and the modal value is about 5 h per year. The modal value of the failure index is about 4 failures per 1000 MV/LV transformers.

Fig. 5. Histogram, boxplot and a pdf obtained by means of KDE (continuous line) and KDEw with the weight  $waga_{SN\_LK}$  (interrupted line) for the failure index  $w_{Tr SN/nN}$  and for the interruption duration  $t_{Tr SN/nN}$  in MV/LV transformers

4.21

1.49

 $t_{Tr\,SN/nN}$  [h]

5.65

5.77

6.89

13.62

# 4. Conclusions

Thorough analysis of the power network failure rate on the basis of exploitation data collected over several years is a key issue for the evaluation of the network conditions. Results of such analyses are important for distribution companies, which can locate weak points in networks, optimize inspection timetables for particular devices and work towards increasing reliability.

The statistical analyses carried out in the study confirm that nonparametric methods are suitable for network reliability evaluation, especially that in practice the number of data is small. The results of non-parametric analysis, including those based on kernel estimators, are both credible and lucid.

Utilizing a few different types of graphic representations of the power network reliability data obtained by non-parametric methods is a novelty aimed at a simultaneous visualization of a number of statistical measures of a variable distribution under analysis. The graphs shown in this paper can be further extended to include other elements, such as distributions obtained by means of parametric methods.

The analysis of failures in MV networks indicates high dispersion in the values of failure indices and interruption durations among the distribution companies included in the study. The modal value for the MV overhead lines was about 8 failures per 100 km of lines with the failure duration of about 3.5 hours per year. In the case of cable lines the modal value was 7 failures per 100 km of lines with an average failure duration of about 1.7 hours per year. The MV/LV transformers prove to be more reliable, since the modal value of the failure index distribution is 0.4 failures per year per 100 MV/LV transformers, with an average failure duration of 5 h.

# References

- 1. 6th CEER Benchmarking Report on the Quality of Electricity and Gas Supply. Brussels: CEER, 2016.
- Billinton R, Allan R. Reliability Evaluation of Power Systems. Second edition. New York: Plenum Press, 1996, https://doi.org/10.1007/978-1-4899-1860-4.
- 3. Briš R, Byczanski P, Goňo R, Rusek S. Discrete maintenance optimization of complex multi-component systems. Reliability Engineering & System Safety 2017; 168: 80-89, https://doi.org/10.1016/j.ress.2017.04.008.
- 4. Brown R, Ochoa J. Distribution system reliability: default data and model validation. IEEE Transactions on Power Systems 1998; 13: 704 -709, https://doi.org/10.1109/59.667403.
- Chojnacki A. Analiza niezawodności eksploatacyjnej elektroenergetycznych sieci dystrybucyjnych. Kielce: Wyd. Politechniki Świętokrzyskiej, 2013.
- Ilie I, Hernando-Gil I, Djokic S. Reliability equivalents of LV and MV distribution networks. IEEE International Energy Conference and Exhibition ENERGYCON 2012; 343-348, https://doi.org/10.1109/EnergyCon.2012.6347779.
- Kornatka M. Assessment of working conditions of 110 kV line. 16th International Scientific Conference on Electric Power Engineering 2015; 296-300.
- Kornatka M, Gawlak A. Comparative Analysis of Operating Conditions in Polish Medium-voltage and 110 kV Networks. Proceedings of the 8th International Scientific Symposium on Electrical Power Engineering 2015; 57-60.
- 9. Kornatka M. The weighted kernel density estimation methods for analysing reliability of electricity supply. 17th International Scientific Conference on Electric Power Engineering 2016; 2-5, https://doi.org/10.1109/EPE.2016.7521729.
- Kolcun M, Kornatka M, Gawlak A, Čonka Z. Benchmarking the reliability of medium-voltage lines. Journal of Electrical Engineering 2017; 68(3): 212-215, https://doi.org/10.1515/jee-2017-0031.
- 11. Kulczycki P. Estymatory jądrowe w analizie systemowej. Warszawa: WNT, 2005.
- 12. Müller H, Wang J. Density and failure rate estimation with application to reliability. Contribution to the Encyclopedia of Statistics in Quality and Reliability. Department of Statistics University of California; 2007.
- Paska J. Chosen aspects of electric power system reliability optimization. Eksploatacja i Niezawodnosc Maintenance and Reliability 2013; 15 (2): 202-208.
- 14. Paska J. Niezawodność systemów elektroenergetycznych. Warszawa: Oficyna Wyd. Politechniki Warszawskiej, 2005.
- 15. R Core Team Copyright C. Środowisko i program R, 1999-2017. Available: https://cran.r-project.org.
- 16. Saleh J, Marais K. Highlights from the early (and pre-) history of reliability engineering. Reliability Engineering & System Safety 2006; 91: 249-256, https://doi.org/10.1016/j.ress.2005.01.003.
- 17. Sheather S, Jones M. A reliable data-based bandwidth selection method for kernel density estimation. Journal of the Royal Statistical Society. Series B 1991; 53(3): 683-690.
- 18. Silverman B. Density Estimation for Statistics and Data Analysis. Chapman and Hall, 1986, https://doi.org/10.1007/978-1-4899-3324-9.
- 19. Statystyka elektroenergetyki polskiej, Warszawa: Agencja Rynku Energii S.A. 2012-2016.
- 20. Turlach B. Bandwidth selection in kernel density estimation: A rewiew. Working Paper. Université catholique de Louvain 1994.
- 21. Venables W, Ripley B. Modern Applied Statistics with S. New York: Springer, 2002, https://doi.org/10.1007/978-0-387-21706-2.
- Wand M, Jones M. Kernel Smoothing. Vol. 60 of Monographs on Statistics and Applied Probability London: Chapman and Hall, 1995, https://doi.org/10.1007/978-1-4899-4493-1.
- 23. Wasserman L. All of Nonparametric Statistics. New York: Springer, 2007.

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# Gökhan GÖKDERE

# TIME-DEPENDENT SYSTEM RELIABILITY UNDER STRESS-STRENGTH SETUP

# OBLICZANIE ZMIENNEJ W CZASIE NIEZAWODNOŚCI SYSTEMU NA PODSTAWIE MODELU WYTRZYMAŁOŚCI NA OBCIĄŻENIA

Consider a system which has n independent components whose time dependent strengths  $Y_1(t), Y_2(t), \dots, Y_n(t)$  are independent identically distributed random processes. Let random processes  $X_1(t), X_2(t), \dots, X_m(t)$  denote the common multiple stresses experienced by the components at time t. The reliabilities of the components in the system can chance as a result of their deterioration or in consequence of variable stresses over time. Degradation in components reliabilities in the system can lead to the degradation of the entire system reliability. In this paper, we propose a new method for determining the time dependent component reliability of the system under stress-strength setup. The proposed method provides a simple way for evaluating the reliability of the system at a certain time period. Computational results are also presented for the reliability of coherent system and consecutive k-out-of-n system.

Keywords: time dependent reliability, stress-strength model, coherent system, consecutive k -out-of-n system.

Rozważmy system, który posiada n niezależnych elementów, z których każdy charakteryzuje się zmienną w czasie wytrzymałością  $Y_1(t), Y_2(t), ..., Y_n(t)$ , która stanowi niezależny proces losowy o identycznym do pozostałych rozkładzie. Niech procesy losowe  $X_1(t), X_2(t), ..., X_m(t)$  oznaczają wielorakie obciążenia powszechnie oddziałujące na elementy systemu w danym czasie t. Niezawodność elementów w systemie może ulegać zmianie w wyniku ich deterioracji lub w wyniku oddziaływania zmiennych w czasie obciążeń. Pogorszenie niezawodności komponentów systemu może prowadzić do obniżenia niezawodności całego systemu. W niniejszym artykule proponujemy nową metodę określania zmiennej w czasie niezawodności składowych systemu na podstawie modelu obciążeń i odpowiadających im wartości wytrzymałości. Zaproponowana metoda zapewnia prosty sposób oceny niezawodności systemu w pewnym okresie czasu. Przedstawiono również wyniki obliczeniowe dotyczące niezawodności systemu koherentnego oraz systemu szeregowego typu k -z- n .

*Słowa kluczowe:* zmienna w czasie niezawodność, model wytrzymałości na obciążenia, system koherentny, system szeregowy k -z- n.

# 1. Introduction

In engineering applications, stress-strength models are of special importance. A technical system may be subjected to several stresses such as pressure, temperature and corrosion and the survival of the system heavily depends on its strength. In the simplest terms, stress-strength model can be described as an assessment of the reliability of the component in terms of X and Y random variables where X is the random "stress" experienced by the component and Y is the random "strength" of the component available to overcome the stress. From this simplified explanation, the reliability of the component is the probability that the component is strong enough to overcome the stress applied on it. Extensive works have been done for the reliability of the component and its estimation under different choices for stress and strength distributions [4, 8, 10, 12].

Traditionally, stress and strength random variables are considered to be both static when available data on X and Y are considered not to involve the time of system operation. But in real-life reliability studies, the status of a stress-strength system clearly changes dynamically with time. This problem may be achieved by modeling at least one of the stress or strength quantities as time-dependent [2, 3, 5, 6, 7, 9, 13].

In some cases, the reliabilities of the components in the system depend on the effect of several stresses which cause degradation. Structurally, the reliability of the system depends on the reliability of its components. Thus, degradation in components reliabilities in the system can lead to the degradation of the entire system reliability. In this paper, we aim to propose a new method for computing the timedependent reliability of the system using its time-dependent components reliabilities under stress-strength setup. A method is presented for the case in which the system consists of n independent components whose time-dependent strengths are independent identically distributed random processes and these components are subjected to m common multiple random stresses over time. We also note that the research concerns only non-renewable systems.

The rest of this paper is organized as follows. Section 2 gives some information about coherent systems and consecutive k-outof-n systems. In section 3, we explain the proposed method for evaluation of the component's time-dependent reliability under the stress-strength setup. Section 4 contains some numerical results on the time-dependent reliability of the four components. In section 5, we compute time-dependent reliability of coherent and consecutivek systems with four components.

k systems with four components.

# 2. Coherent systems and consecutive k -out-of-n systems

In this section, we analyze coherent systems and consecutive k-out-of-n : F and G systems.

A coherent system consists of n components such that the system and each component may only be in one of two possible states, working or failed, can be described as follows. Suppose that  $x_i$ , i = 1, 2, ..., n, the state of component i, is a random variable such that:

$$x_i = \begin{cases} 1 & \text{if component } i \text{ works,} \\ 0 & \text{if component } i \text{ is failed.} \end{cases}$$

Let  $\phi(\mathbf{x})$ , be the structure function of the system. Then,

$$\phi(\mathbf{x}) = \begin{cases} 1 & \text{if the system works,} \\ 0 & \text{if the system is failed,} \end{cases}$$

where  $\mathbf{x} = (x_1, x_2, ..., x_n)$  which represents the states of all components and is called the component state vector.

A system is said to be coherent if each component is relevant and the structure function  $\phi(\mathbf{x})$  is non-decreasing in each argument. For more details, we refer to [1].

The reliability of a coherent system can be computed from the structure function  $\phi(\mathbf{x})$  as  $R_{\phi}(\mathbf{p}) = P(\phi(\mathbf{x}) = 1) = E\phi(\mathbf{x})$ , where  $\mathbf{p} = (p_1, ..., p_n) = P(\mathbf{x}_1 = 1, ..., \mathbf{x}_n = 1)$ .

**Example 1.** Consider the four-component serial-parallel system whose structure is illustrated by Figure 1. Its structure function can be expressed as:

$$\phi(x_1, x_2, x_3, x_4) = \min(x_1, \max(x_2, x_3, x_4)).$$



Fig. 1. Four-component serial-parallel system

The system reliability which is the stochastic independence of components is given by:

$$R_{\phi}(p_1, p_2, p_3, p_4) = E\left(\min\left(x_1, \max\left(x_2, x_3, x_4\right)\right)\right)$$
$$= p_1\left(p_2 + p_3 + p_4 - p_2p_3 - p_2p_4 - p_3p_4 + p_2p_3p_4\right)$$
(1)

A consecutive k-out-of-n: F system consists of n ordered components such that the system fails if and only if at least k consecutive components fail. Another special type of system related to the consecutive k-out-of-n: F system is the consecutive k-out-of-n: G system. A consecutive k-out-of-n: G system is an ordered sequence of n components such that the system works if and only if at least k consecutive components work. Consecutive k-out-of-n: F and G systems are divided into linear and circular systems correspond to the components arranged along a line or circle.

Lambiris and Papastavridis [14] developed an exact formulas for the reliability of a consecutive k-out-of-n : F system with n linearly or circularly arranged independent and identically distributed components. But in some cases components are not necessarily identical. Therefore, Zuo and Kuo [15] obtained the following closed-form equations for the reliability of a linear consecutive k-out-of-n : F system, say  $R_{LF}(k,n,p_i)$ , and circular consecutive k-out-of-n : F system, say  $R_{CF}(k,n,p_i)$ , respectively. Here, the value  $p_i$ , i = 1,2,...,n is called the reliability of the i th component.

$$R_{LF}(k,n,p_i) = 1 - \sum_{i=1}^{n-k+1} \left( p_{i+k} \prod_{j=i}^{i+k-1} (1-p_j) \right), \quad p_{n+1} \equiv 1, \quad k \le n \le 2k, \quad (2)$$

where i = 1, 2, ..., n and  $R_{LF}(k, n, p_i) = 1$  for  $0 \le n \le k$ , and

$$R_{CF}(k,n,p_i) = 1 - \sum_{i=1}^{n} \left( p_{i+k} \prod_{j=i}^{i+k-1} (1-p_j) \right) - \prod_{i=1}^{n} (1-p_i), \quad k < n \le 2k+1,$$
(3)

where i = 1, 2, ..., n,  $p_j \equiv p_{j-n}$  for j > n,  $R_{CF}(k, n, p_i) = 1$  for  $0 \le n < k$  and  $R_{CF}(k, n, p_i) = 1 - \prod_{i=1}^{n} (1 - p_i)$  for n = k.



Fig. 2. Linear consecutive 2 -out-of-4: F system

**Example 2.** Consider the linear consecutive 2-out-of-4: F system in Figure 2. It consists of a sequence of four components along a line such that the system is failed if and only if at least two consecutive components in the system are failed. Using Equation (2), one obtains the system reliability as:

$$R_{LF}(2,4,p_1,p_2,p_3,p_4)$$

$$=1-\left[p_{3}(1-p_{1})(1-p_{2})+p_{4}(1-p_{2})(1-p_{3})+(1-p_{3})(1-p_{4})\right](4)$$

**Example 3.** Consider the circular consecutive 2-out-of-4: F system. It consists of a sequence of four components along a circle such that the system is failed if and only if at least two consecutive components in the system are failed. Using Equation (3), one obtains the system reliability as:

$$R_{CF}(2,4,p_1,p_2,p_3,p_4) = 1 - [p_3(1-p_1)(1-p_2) + p_4(1-p_2)(1-p_3) + p_1(1-p_3)(1-p_4) + p_2(1-p_1)(1-p_4)] - (1-p_1)(1-p_2)(1-p_3)(1-p_4)(5)$$

Kuo et al.[11] state that the consecutive k-out-of-n : G and F systems are the duals of each other. Therefore, the reliability of the linear consecutive k-out-of-n : G system, denoted by  $R_{LG}(k, n, p_i)$ , is then equal to  $1 - R_{LF}(k, n, 1 - p_i)$  and the reliability of the circular

consecutive k -out-of-n : G system, denoted by  $R_{CG}(k, n, p_i)$ , is then equal to  $1 - R_{CF}(k, n, 1 - p_i)$ .

**Example 4.** Consider the linear consecutive 2 -out-of- 4 : *G* system. It consists of a sequence of four components along a line such that the system is good if and only if at least two consecutive components in the system are good. Using Equation (4) for  $p_i = 1 - p_i$ , i = 1, 2, 3, 4, one obtains the system reliability as:

$$R_{LG}(2,4,p_1,p_2,p_3,p_4) = p_1 p_2 (1-p_3) + p_2 p_3 (1-p_4) + p_3 p_4 \quad (6)$$

**Example 5.** Consider the circular consecutive 2-out-of-4: *G* system. It consists of a sequence of four components along a circle such that the system is good if and only if at least two consecutive components in the system are good. Using Equation (5) for  $p_i = 1 - p_i$ , i = 1, 2, 3, 4, one obtains the system reliability as:

$$R_{CG}(2,4,p_1,p_2,p_3,p_4)$$

 $=p_{1}p_{2}\left(1-p_{3}\right)+p_{2}p_{3}\left(1-p_{4}\right)+p_{3}p_{4}\left(1-p_{1}\right)+p_{1}p_{4}\left(1-p_{2}\right)+p_{1}p_{2}p_{3}p_{4}\left(7\right)$ 

From the equations for system reliability given above, we can see that the reliability of a system with components whose reliabilities are not necessarily identical is a function of  $p_i$  and the component reliabilities are constant. But, the reliabilities of the components in the system can change as a result of their deterioration or in consequence of variable stresses over time. The components may not fail completely, but can degrade. Degradation in components reliability can lead to the degradation of the entire system reliability. Consideration of dynamic component reliability under stress-strength setup offers realistic application to real life applications.

In the following section, we propose a new approach for determining the dynamic components reliabilities of the system when it is subjected to a common multiple stresses over time.

### 3. Proposed method

Consider a system that consists of *n* independent components whose deteriorating strengths  $Y_i(t) \ge 0$ , i = 1, 2, ..., n are independent identically distributed random processes with continuous cumulative distribution function  $G_{i(t)}(y) = P\{Y_i(t) \le y\}$ . Assume that these components are subjected to common multiple stresses  $X_j(t) \ge 0$ , j = 1, 2, ..., m. Let the stresses are independent random processes having cumulative distribution function  $F_{j(t)}(x) = P\{X_j(t) \le x\}$ .

Let us defined the random lifetime,  $T_i$ , of the component *i* as:

$$T_{i}(t) = \inf \{t : t \ge 0, X_{1:m}(t) < Y_{i}(t)\},$$
(8)

where:

$$X_{1:m}(t) = \min(X_1(t), ..., X_m(t)).$$

In this framework, the component *i* is fail if  $Y_i(t) < X_{1:m}(t)$ . Because the *i* th component's strength remains weak in all stresses.

Given that component *i* is of age *t*, the remaining life after time *t* is random. For a specific time period [t, t+h], the reliability of the component *i*,  $p_i(t)$ , which is defined as the probability of surviving at time t+h, follows from (8) that:

$$p_i(t) = P\left\{T_i(t) > t + h | T_i(t) > t\right\}$$

The above conditional probability function depends on h and event  $T_i(t) > t$ . Thus, from the definition of conditional probability we have:

$$p_i(t) = \frac{P\{T_i(t) > t + h\}}{P\{T_i(t) > t\}} = \frac{1 - H_i(t + h)}{1 - H_i(t)}$$
(9)

where  $H_i(t) = P\{T_i(t) \le t\}$ , i = 1, 2, ..., n. Clearly, as  $H_i(t)$  is absolutely continuous, the probability distribution function  $h_i(t) = \frac{d}{dt}H_i(t)$  exists almost everywhere. Then, we have main exponential formula:

$$H_i(t) = 1 - \exp\left(-\int_0^t \lambda_i(u) du\right)$$
(10)

where  $\lambda_i(u)$ , i = 1, 2, ..., n is the corresponding failure rate.

Then, using Equation (10) in (9), we can obtain the i th component's reliability as follows:

$$p_i(t) = \exp\left(-\int_t^{t+h} \lambda_i(u) du\right).$$
(11)

An important tool for system reliability in our proposed method is the failure rate that describes the component reliability. Therefore, the shape of the failure rate plays an important role under stress-strength setup of the system.

Assume that the failure rate,  $\lambda_i(t)$ , is increasing as a result of their deterioration and common multiple stresses. As the finite mean of  $Y_i(t)$  and  $X_j(t)$ ; say  $EY_i(t)$  and  $EX_j(t)$  respectively, exists the

 $\lambda_i(t)$  can be expressed as:

$$\lambda_i(t) = \left(\sum_{j=1}^m \left(EY_i(t) - EX_j(t)\right) \psi_{EY_i(t_i^j) - EX_j(t_i^j) > 0}\right)^{-1}, \quad (12)$$

where  $\psi$  is an indicator function such that:

$$\psi_A = \begin{cases} 1, & \text{if event } A \text{ occurs at time } t \\ 0, & \text{if event } A \text{ does not occurs at time } t. \end{cases}$$

Using Equation (12) in (11), when running into time t, the  $p_i(t)$  can be obtained under stress-strength setup as:

$$p_{i}(t) = \exp\left(-\int_{t}^{t+h} \left(\sum_{j=1}^{m} \left(EY_{i}(u) - EX_{j}(u)\right)\psi_{EY_{i}\left(t_{i}^{j}\right) - EX_{j}\left(t_{i}^{j}\right) > 0}\right)^{-1} du\right) \cdot (13)$$

It should be noted that:

1) If the failure rate  $\lambda i(t)$  is increasing (decreasing) in t, then the reliability  $p_i(t)$  is decreasing (increasing) in [0,1]. Therefore, the system is decreasing (increasing).

2) The range of  $t_i^j$  is  $0 < t_i^j < \infty$ , which represents the time that *j* th stress is equal *i* th component strength.

Thus, the dynamic system reliability under stress-strength setup can be computed by substituting the Equation (13) in the equations for system reliability given in Section 2.

In the following section, we use parametric statistical model to compute the dynamic reliability of the components under stressstrength setup.

### 4. Dynamic reliability for four components

In this section, we compute reliability for four components under the stress-strength setup. We assume that all components are subjected to three stresses, which are stochastically increasing in time, whereas its strengths are independent identically distributed random variables, which are stochastically decreasing in time. We use Weibull process for stress and strength variates, because it is a useful model for events that are changing over time.

Let,  $Y_i(t)$ , i = 1,2,3,4 be a Weibull processes whose distribution is:

$$G_{i(t)}(y) = 1 - \exp\left\{-\left(\frac{y}{\alpha_i(t)}\right)^{\beta_i}\right\}, y > 0,$$

where  $\alpha_i(t) > 0$ ,  $\beta_i > 0$ . Because of  $\alpha_i(t)$  decreases over time,

let  $\alpha_i(t) = 1/\alpha_i t$  then we have the finite mean of  $Y_i(t)$  as:

$$EY_i(t) = \frac{1}{\alpha_i t} \Gamma\left(1 + \frac{1}{\beta_i}\right).$$
(14)

Let,  $X_j(t)$ , j = 1,2,3 be a Weibull processes whose distribution is:

$$F_{j(t)}(x) = 1 - \exp\left\{-\left(\frac{x}{\theta_j(t)}\right)^{\lambda_j}\right\}, \ x > 0$$

where  $\theta_j(t) > 0$ ,  $\lambda_j > 0$ . Because of  $\theta_j(t)$  increasing over time, let  $\theta_j(t) = \theta_j t$  then we have the finite mean of  $X_j(t)$  as:

$$EX_{j}(t) = \left(\theta_{j}t\right)\Gamma\left(1 + \frac{1}{\lambda_{j}}\right).$$
(15)

Then, using (14) and (15) in (13) we have:

$$p_i(t) = \exp\left(-\int_{t}^{t+h} \left(\sum_{j=1}^{3} \left(\frac{1}{\alpha_i t} \Gamma\left(1+\frac{1}{\beta_i}\right) - \left(\theta_j t\right) \Gamma\left(1+\frac{1}{\lambda_j}\right)\right) \psi_{EY_i(t_i^j) - EX_j(t_i^j) > 0}\right)^{-1} du\right).$$
(16)

where i = 1, 2, 3, 4.

Using Equation (16), we can obtain dynamic reliability for four components under stress-strength model. The reliability of the components decreases over time, depending on the various selection of the

parameters  $\alpha_i, \beta_j, \theta_j$  and  $\lambda_j$ . For an illustration, let  $\alpha_1=0.02, \beta_1=0.2$  and  $\theta_1=0.8, \lambda_1=0.6; \theta_2=1.2, \lambda_2=0.6; \theta_3=1.1, \lambda_3=1.6$ . Then  $t_1^1 = 70.6031$ ,  $t_1^2 = 57.6472$  and  $t_1^3 = 77.9985$ . This implies that after the time  $t_1^2$  the stress  $X_2(t)$  is above of the strength  $Y_1(t)$ , after the time  $t_1^3$  the stress  $X_3(t)$  is above of the strength  $Y_1(t)$ . As a result, we observe that the 1th component strength cannot resist all of the stresses after the time  $t_1^3$  and component 1 is assigned to be completely failed.

In Table 1, we give the  $t_i^j$ , i = 1,2,3,4; j = 1,2,3, time for various selection of  $\alpha_i$ ,  $\beta_j$ ,  $\theta_j$  and  $\lambda_j$ . From the table we observe that the component 4 has the highest reliability compared to other component and component 3 has the lowest reliability compared to other components.

Table 1. The  $t_i^j$  time that *j* th stress is equal *i* th component strength ( $\theta_1$ =0.8,  $\lambda_1$ =0.6;  $\theta_2$ =1.2,  $\lambda_2$ =0.6;  $\theta_3$ =1.1,  $\lambda_3$ =1.6)

$\alpha_1 = 0.02, \\ \beta_1 = 0.2$	$\alpha_2 = 0.03, \ \beta_2 = 0.2$	$\alpha_3$ =0.01, $\beta_3$ =0.3	$\alpha_4$ =0.01, $\beta_4$ =0.2
$t_1^1 = 70.6031$	$t_2^1 = 57.6472$	$t_3^1 = 27.7374$	$t_4^1 = 99.8478$
$t_1^2 = 57.6472$	$t_2^2 = 47.0687$	$t_3^2 = 22.6475$	$t_4^2 = 81.5254$
$t_1^3 = 77.9985$	$t_2^3 = 63.6855$	$t_3^3 = 30.6428$	$t_4^3 = 110.307$

In Table 2, we compute dynamic reliability for four components for the parameters given in Table 1. From the table we observe that component 1 can resist all three stresses until the time period [72,74), component 2 can resist all three stresses until the time period [60,62), component 3 can resist all three stresses until the time period [24,26), and component 4 can resist all three stresses until the time period [108,110), after the these time periods all four components are assigned to be completely failed component.

We have everything in place now for obtaining the dynamic reliability of the components under stress-strength setup, which is crucial for reliability of the system. In the following section, we compute dynamic reliability of the system with four components under stressstrength setup.

Table 2. Dynamic reliability for four components for selected time period  $\begin{bmatrix} t, t+h \end{bmatrix}$ 

[t,t+h)	$p_1(t)$	$p_2(t)$	$p_{3}(t)$	$p_4(t)$
0-2	0.9998	0.9998	0.9992	0.9999
12-14	0.9985	0.9977	0.9876	0.9992
24-26	0.9967	0.9947	0.8996	0.9985
36-38	0.9941	0.9887	0	0.9975
48-50	0.9883	0.9647	0	0.9962
60-62	0.9687	0.6780	0	0.9942
72-74	0.8196	0	0	0.9901
84-86	0	0	0	0.9794
96-98	0	0	0	0.9441
108-110	0	0	0	0.3611

# 5. Reliability for coherent and consecutive *k*-out-of-*n* systems with four components

In this section, using dynamic reliability for four components given in the previous section, we compute dynamic reliability of

Table 3. Dynamic reliability for systems for selected time period [t,t+h]

[t,t+h)	$R(p_i(t))$	$R_{LF}(2,4,p_i(t))$	$R_{CF}(2,4,p_i(t))$	$R_{LG}(2,4,p_i(t))$	$R_{CG}(2,4,p_i(t))$
0-2	0.9998	1.	1.	1.	1.
12-14	0.9985	0.9999	0.9999	0.9999	0.9999
24-26	0.9966	0.9993	0.9992	0.9991	0.9996
36-38	0.9940	0.9862	0.9862	0.9828	0.9940
48-50	0.9881	0.9610	0.9610	0.9534	0.9881
60-62	0.9668	0.6740	0.6740	0.6567	0.9668
72-74	0.8114	0	0	0	0.8114
84-86	0	0	0	0	0
96-98	0	0	0	0	0
108-110	0	0	0	0	0

# coherent systems and consecutive k-out-of-n: F(G) systems with four components. In Table 3, we compute the dynamic reliability for coherent system and consecutive k-out-of-n: F(G) systems given in Section 2, using the $p_i(t)$ , i = 1, 2, 3, 4 values given in Table 2.

# 6. Conclusion

In this paper, it is theoretically assumed that a system which consists of n components operates under m common multiple stresses. We provide a new method for computing the time-dependent reliability of the system using its time-dependent components reliabilities under stress-strength setup. The proposed method described here is a simple and clearly show the chance of component and system reliability depending on time.

# References

- 1. Barlow R E, Proschan F. Statistical Theory of Reliability and Life Testing: Probability Models, To Begin With, 1981.
- Basu A P, Ebrahimi N. On the reliability of stochastic systems. Statist. Probab. Lett. 1983; 1: 265-267, https://doi.org/10.1016/0167-7152(83)90042-1.
- Basu S, Lingham R T. Bayesian estimation of system reliability in Brownian stress-strength models. Ann. Inst. Statist. Math. 2003; 55: 7-19, https://doi.org/10.1007/BF02530482.
- 4. Chandra S, Owen D B. On estimating the reliability of a component subject to several different stresses (strengths). Naval Res. Log. Quart. 1975; 22: 31-40, https://doi.org/10.1002/nav.3800220104.
- 5. Ebrahimi N. Two suggestions of how to define a stochastic stress-strength system. Statist. Probab. Lett. 1985; 3: 295-297, https://doi. org/10.1016/0167-7152(85)90058-6.
- Ebrahimi N, Ramallingam T. Estimation of system reliability in Brownian stress-strength models based on sample paths. Ann. Inst. Statist. Math. 1993; 45: 9-19, https://doi.org/10.1007/BF00773665.
- 7. Eryılmaz S. On stress-strength reliability with a time-dependent strength, J. Qual. Reliab. Eng. 2013, 2013: 1-6.
- 8. Eryılmaz S, İşçioğlu F. Reliability evaluation for a multi-state system under stress-strength setup. Commun. Statist. Theor. Meth. 2011; 40: 547-558, https://doi.org/10.1080/03610920903411242.
- 9. Gokdere G, Gurcan M. New Reliability Score for Component Strength Using Kullback-Leibler Divergence. Eksploatacja i Niezawodnosc Maintenance and Reliability 2016; 18: 367-372, https://doi.org/10.17531/ein.2016.3.7.
- Kotz S, Lumelskii Y, Pensky M. The Stress-Strength Model and its Generalizations. Theory and Applications. Singapore: World Scientific, 2003, https://doi.org/10.1142/9789812564511.
- 11. Kuo W, Zhang W, Zuo M. A consecutive-k-out-of-n: G system: The mirror image of a consecutive-k-out-of-n: F system. IEEE Transactions on Reliability 1990; R-39(2): 244-253, https://doi.org/10.1109/24.55888.
- 12. Nadarajah S, Kotz S. Reliability for some bivariate exponential distributions. Mathematical Problems in Engineering 2006; 2006: 1-14.
- 13. Whitmore G A. On the reliability of stochastic systems: a comment. Statist. Probab. Lett. 1990; 10: 65-67, https://doi.org/10.1016/0167-7152(90)90113-L.
- Lambiris M, Papastavridis S. Exact reliability formulas for linear & circular consecutive-k-out-of-n: F systems. IEEE Transactions on Reliability 1985; R-34(2): 124-126, https://doi.org/10.1109/TR.1985.5221969.
- Zuo M J, Kuo W. Design and performance analysis of consecutive-k-out-of-n structure. Naval Research Logistics 1990; 37: 203-230, https:// doi.org/10.1002/1520-6750(199004)37:2<203::AID-NAV3220370203>3.0.CO; 2-X.

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# APPLICATION OF NEURAL RECONSTRUCTION OF TOMOGRAPHIC IMAGES IN THE PROBLEM OF RELIABILITY OF FLOOD PROTECTION FACILITIES

# ZASTOSOWANIE NEURONOWEJ REKONSTRUKCJI OBRAZÓW TOMOGRAFICZNYCH W PROBLEMATYCE NIEZAWODNOŚCI ZABEZPIECZEŃ PRZECIWPOWODZIOWYCH\*

The article presents an innovative concept of enhancing the flood embankments and landfills monitoring. The key advantage of such a solution is to obtain a more detailed distribution of components within a flood barrier. It leads to more early and sufficient threat detection, considering the exploitation of the building, thus - a vast enhancement of an embankment's performance. The method is based on implementing a neural system, composed of a number of parallelly-working neural networks. Each of them generate a singular point of final output view. By implementing such monitoring measures it is possible to successfully reconstruct two-and-three dimensional models of flood barriers and dams - including possible breaches and damages within its inner structure. An important advantage of such a solution is the possibility of replacing the systems that monitor hydrotechnical facilities pixel-by- pixel by neural imaging. The performed research leads to solving the problem of low resolution of such images. As this problem was of crucial value to tomographic imaging method, it was a main obstacle to the development of neural reconstruction method. Moreover, as the results may be obtained in real-time and at various levels, these new functionalities stand out in comparison to currently used methods for monitoring protective banks.

*Keywords:* electric tomography, flood embankments and landfills, hydrotechnical facilities exploitation, neural networks, numerical methods.

W artykule zaprezentowano nowatorską koncepcję usprawnienia monitoringu wałów i zapór przeciwpowodziowych. Główną przewagą nowego rozwiązania nad znanymi metodami jest uzyskanie dokładniejszego rozkładu komponentów wnętrza zapory, co zasadniczo przyczynia się do wczesnego i niezawodnego wykrycia zagrożeń związanych z eksploatacją tego typu budowli. Dzięki temu, zastosowanie nowej metody spowoduje wzrost niezawodności zabezpieczeń przeciwpowodziowych. W opisywanej metodzie założono wytrenowanie systemu neuronowego złożonego z wielu działających równolegle sieci neuronowych, z których każda generuje pojedynczy punkt obrazu wyjściowego. Powyższy sposób, uwzględniający jednoczesne zastosowanie wielu sieci neuronowych, umożliwia skuteczną realizację trudnych zagadnień rekonstrukcji obrazów dwu i trój-wymiarowych, w tym obrazowanie uszkodzeń i przecieków wnętrza zapór przeciwpowodziowych. Ważną zaletą prezentowanej metody jest możliwość zastąpienia obrazowaniem neuronowym wielu innych, obecnie stosowanych systemów, które monitorują budowle hydrotechniczne w sposób punktowy. Przeprowadzone badania umożliwiają rozwiązanie problemu niskiej rozdzielczości obrazów tomograficznych, co stanowi główną barierę rozwoju tych metod w odniesieniu do dużych budowli ziemnych. Poprawa rozdzielczości rekonstruowanych obrazów, a także możliwość ich uzyskiwania w różnych przekrojach w czasie rzeczywistym, są nowymi funkcjonalnościami, które wyróżniają obrazowanie neuronowe na tle obecnie stosowanych metod monitoringu wałów i zapór przeciwpowodziowych.

*Slowa kluczowe*: tomografia elektryczna, zapory i wały przeciwpowodziowe, eksploatacja budowli hydrotechnicznych, sieci neuronowe, metody numeryczne.

# 1. Introduction

The exploitation of flood defences - such as dams and flood banks - is of key value that heavily impacts the security of people, animals and plants that lay within the area of the object. There are two main types of issues that may appear as a result of improper exploitation of such pieces of infrastructure. The first threat is a physical damage of the embankment, which may result in a breach. The other is the leakage of such a structure - in case of reservoirs that contain fluid chemical compound waste it might lead to a vast range of contamination. Both types of breaches may result in [25]:

- endangering both people and animals' lives and cause an evacuation;
- closing public responsibility facilities, such as administration, hospitals or schools;
- increasing the possibility of epidemic, epizootic or epifitozic outbreaks;
- increasing the possibility of a plague of insects or rodents;
- destruction of stock and harvest in agricultural holdings (weakening the economical state of food industry, an increase of food supplies prices, a need to compensate the entrepreneurs who process and sell food);

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- destruction and damaging buildings (houses, utility buildings and public utility buildings);
- infrastructural damage (including roads, bridges, fly-overs, tunnels, dams, pumping stations, hydrotechnical devices, water mains and sewer networks-related devices);
- destruction in energy-production infrastructure including generation, transmission and distribution of electricity and heating;
- disruptions in the functioning of communication and teleinformation systems;
- damage dealt to communication traction, accidents caused in industrial plants;
- malfunctioning of the fuel distribution system;
- possible increase in criminality as well as an increased number of common offenses (such as burglary, robberies, property destruction).

What is more, the penetration of chemical waste through embankments creates such hazards as the possibility of local environment contamination, as well as damage to installations and technical equipment. Also, it may cause a release of harmful substances and - consequently - a degradation of the natural environment.

Floods are considered to be natural disasters that cause particularly many tragedies [3, 7]. One of the means of ensuring the safety of flood-endangered areas near the flotation tailings landfills and rivers is to raise the flood embankments [18]. Considering the insufficient filtration capacity of the embankment, the high water level may cause leaks, which results in partial or complete destruction of the hydrotechnical building [19].

As breakdowns lead to serious consequences, such technical facilities such as dams, embankments and other flood defences are equipped with various systems to increase their reliability. Embankment and dam exploitation systems include both adequate means of service as well as a code of operating activities designed as a set of strict procedures and instructions. This kind of guide set a universal standard which should be followed. These include, among others, tips regarding the frequency and method of inspections, tests, measurements and technical inspection of the facility, as well as a list of hydrotechnical building elements to be observed - along with a list of parameters that should be measured. The aforementioned registry constitute evidence of keeping constant observation, monitoring and measurements which are key elements of embankments and flood control dams. In most cases, flood protection security systems are extensive and vastly complex. They consist of many subsystems whose proper functioning affects the reliability of these objects. Typical subsystems included in embankments and flood control systems include hydrological protection systems, alarms, energy systems, mechanical water flow regulation systems and, as well as computer-aided decision support software.

In order to ensure effective monitoring of these systems, appropriate methods should be used. Computer-aided decision support systems play a special role in the integration of other pieces of software as well as decision-making automation. The latter consists of identifying and forecasting specific threats together with the probability of their occurrence. The final decision regarding the response to the results is always made by a human. Below, there are listed currently used monitoring methods - in the context of the Extraction Waste Treatment Facility Żelazny Most KGHM POLSKA MIEDŹ S.A. It is the largest hydrotechnical facility in Poland and one of the largest facilities of this type in the world. The monitoring methods used there can be divided into two groups: means related to the current behavior of the structure and its reliability, and those related to the impact of the structure on the surrounding natural environment. The first group includes the following monitoring methods: visual assessment of technical condition (direct observation carried out by employees),

geodetic monitoring (detection of structural deformation by manual measurements with benchmarks and automatic using micromirrors), geotechnical monitoring (detection of anomalies in the geological structure of the native substrate embankments and reservoirs through deep drilling and pressure probes), hydrogeological monitoring (detection of anomalies which result in embankment leakage by observing piezometric pressures in piezometers installed in the waste mass, embankments and near and far foreground), seismic monitoring (detection of structural stability disturbances by means of accelerometers that are triggered each time they identify vibrations at a certain level), information systems for the analysis of large data sets (Big Data). The prevention on surrounding natural environment include hydrological monitoring (detecting leaks) and chemical monitoring (detection of contamination that affects groundwater).

The global trend of IT and communication technology development is reflected in the increase in the importance of IT flood protection systems. The extensive measurement systems provide a great deal of data collected from different points of flood defence. One of the main tasks of IT systems installed in hydrotechnical facilities is to create mathematical models based on the information provided. Currently used IT systems implement a wide variety of methods. The deterministic methods include the Fellenius one, which makes it possible to assess the degree of embankment stability by dividing the potential landslide mass into vertical blocks (belts). This method is also known as the Petterson-Fellenius or the Swedish method [4]. An example of a statistical quantitative method is the HST model (Hydrostatic-Season-Time). The empirical HST model is widely used for the analysis of various types of measurement data on flood embankments and dams [6]. Another group of methods used to improve the risk of flood barriers breach are probabilistic ones. It may be exemplified by the first order reliability method (FORM), by means of which the mode of longitudinal damage of a long embankment consisting of homogeneous soils can be examined [9]. In order to increase the reliability of earth structures, together with the FORM method the Hasofer-Lind reliability index can be applied [13]. Harmonic analysis is also one of the methods used in exploitation processes [11].

A frequent problem with flood dams is insufficient water filtration causing the so-called sub-penetration. In the literature one can find propositions of methods to calculate the probability that such phenomena will occur [15].

Another group of intelligent stochastic methods used by IT systems in order to increase the reliability of exploitation processes, including embankments and flood barriers, are heuristic methods based on fuzzy logic [14, 22, 24]. Less frequently used methods to obtain the same purpose are: integer linear programming [10], Support Vector Machine [17], non-linear criterion of shear stability [23], and artificial neural networks (ANN) [1, 8]. Currently, the main application area of ANN are predictive issues which aim at enhance exploitation processes by identifying [16] or classifying faults [26].

As previously mentioned, flood protection facilities belong to the category of hydrotechnical constructions. The analysis of procedures and rules of exploiting this type of objects allows to notice one of the main processes that ensure a proper course of operations, being observation of current behavior and phenomena detection. Due to their specificity, they may indicate irregularities threatening the safety of the building. Current methods of monitoring technical facilities such as flood banks and dams have, however, numerous disadvantages. The first of them are apparently high usage costs. Most of the currently used methods require the involvement of specialists, which means that labor is an important element of such expenses. In addition, the measurement systems require investments for repairs, maintenance, spare parts and materials that wear out. Also, an important disadvantage is usually a late threat detection. In the case of systems that are not a component of integrated IT systems, information about the threat reaches the relevant services within a few hours' delay. The delay de-

pends on the frequency with which the readings of the measuring devices are included in the procedures. The effectiveness of monitoring methods that are by now implemented is also insufficient [4, 5]. Due to the point character of the measurements, there is a great uncertainty of the conclusions drawn on their basis. Probes and sensors placed in various places on the embankment do not give the possibility of obtaining full knowledge about its current state. There is a serious risk that defects appearing inside the flood dam (cracks, changes in the internal structure, changes in composition and density of the earth, etc.) will not be detected early enough to enable them to be corrected. In order to get the most complete knowledge about the technical condition of the facility, it is necessary to use many monitoring methods at the same time. In order to simplify the way of monitoring the facility and the application procedure, there is a clear need to develop one effective method, ensuring the speed and reliability of collecting, transferring and processing of information about existing threats. Most of the mentioned disadvantages would be eliminated if it was possible to develop a new method of technical condition assessment that would gather a current stream of data concerning differences in the internal structure of the flood defence. One of the potential methods to achieve this goal is electrical tomography [2, 12]. The tomography generates the image of the tested object interior. This method is mainly used in medicine and material engineering. The main obstacle of tomographic methods development in flood embankments and dams monitoring is the lack of appropriate technology that would provide a significant improvement in image resolution.

This article presents a new approach to the operational problem of object monitoring using neural imaging. Previous attempts to use artificial neural networks in electrical tomography have focused on the use of individual neural networks to process input signals into images. During the research, an improved method of neural tomographic reconstruction was developed. Its characteristic feature is the usage of a neural network system in which each network generates the color of a single pixel on the image grid. Thanks to the original architecture of the intelligent imaging system, a new functionality was obtained with reference to known tomographic methods, which consisted in increasing the resolution of cross-section images of scanned hydrotechnical objects.

# 2. Neural reconstruction of tomographic images

The neural reconstruction of tomographic images presented in this article is a new method aimed at increasing the resolution of images, and thus enhancing the flood protection monitoring effectiveness. The algorithm makes it possible to eliminate the main operational problems of hydrotechnical facilities connected with their monitoring. Tomography supported by a neural system gives new possibilities for surveillance. The presented concept create an accurate, three-dimensional image of the interior of a hydrotechnical building in real time. This is the key functionality that lessens the importance of maintaining the majority of existing subsystems of flood protection monitoring. Currently used monitoring systems (geodetic, geotechnical, hydrological, etc.) relate to obtaining point data regarding selected object parameters. Later on, obtained incomplete information is subject to analysis, both by IT systems and by specialists who perform the final assessment of the dam condition. Such an assessment process has major disadvantages resulting from measuring points, measurement errors, lack of real-time monitoring and subjectivism in evaluating the status of the subject technical object. The method depicted in this article is free from the above restrictions, as it results in obtaining sharp, colorful, three-dimensional images of the interior of the dams and flood dams bodies in high resolution and in real time. The obtained images are easy to analyze because they faithfully reproduce all changes taking place inside flood embankments and dams. Phenomena such as: cracks, changes in the structure of internal layers, moisture increase or density changes are immediately visible. The comparison of images recorded at regular intervals make it possible to determine the pace of changes that are taking place within the structure. This is a very valuable functionality because it provides a solid basis for making accurate and reliable predictions about the sources, directions of development, type and area of damage developing inside the building.

# 3. Neural system to reconstruct tomographic images - modelling

The presented solution is an improvement of the already known electrical tomography. A number of electrodes are placed in the body of the flood embankment. Then, a source of electric current with certain parameters (voltage, current, frequency, amplitude) is connected to different electrodes. The voltage values between the respective electrodes are read and recorded. The aforementioned voltage values are the input vector, on the basis of which the neural system generates images of the interior of the dam. It is assumed that the values of electric parameters read out from electrodes are closely dependent on the material from which the flood defence is made. Any changes in the internal structure of the dam caused by moisture, leakage, structure breakage, landslides and any other anomalies, are reflected in the values of the current-voltage parameters read from the electrodes. To confirm the above assumptions, a mechanism for converting electrical signals into high-resolution color images has been developed.

# 3.1. The means of data gathering

The real-life object of the research was the barrage of the Żelazny Most Flotation Wastes Depository located in the south-western part of Poland between Lubin and Głogów. The reservoir is located in a natural valley between moraine hills in the upper part of the Rudna river catchment. The management of the disposal facility is KGHM "Polska Miedź" S.A. Branch Hydrotechnical Plant in Rudna [21]. The "Żelazny Most" facility is intended for storing flotation waste from the Red Ore Enrichment Plants: Polkowice, Lubin and Rudna. Currently, it is the only place for depositing flotation waste from all mines. Due to the area occupied, the "Żelazny Most" landfill is one of the largest facilities of its kind in the world [20]. The total length of dams surrounding the reservoir is over 14 km. The total area of the landfill is 1410 ha. The height of the dams at the highest point reaches 55 m. The topographic model of the Żelazny Most reservoir is shown in Fig.1.



Fig. 1. Topological model of the Żelazny Most Flotation Wastes Depository

The facility has been equipped with various diagnostic and control-measurement systems, whose task is to ensure a high degree of reliability of the Żelazny Most reservoir. These include: drainage, systems for rapid and emergency dewatering of the basin, embankments and relief wells whose task is to reduce the water pressure in the soil of the ground. Around the "Żelazny Most" facility, constant surveillance is carried out on a regular basis. The monitoring concerns both surface and underground waters. The imperfection of currently used methods of monitoring is their punctuality. By using them, you cannot get cross-sectional images of the interior of the dam. Fig. 2 shows a photo of an earth embankment of the reservoir with visible elements of various measurement systems that provide point data enabling ongoing monitoring of the building.



Fig. 2. Surface of the earth embankment around the Żelazny Most reservoir

The key element of the neural system used to reconstruct tomographic images is a neural controller. Its task is to convert electrical signals into images. A proper set of training data was needed to implement the neural system. Due to the fact that it was not possible to download this type of data directly from the embankment of the Żelazny Most reservoir, a physical model of the flood embankment part was created in the laboratory conditions. By doing so, the examined features of the real object such as: dam material, geometry of shape, proportions of dimensions, water level in tank were reproduced. Thus, research data from many measuring cases was obtained. The data included sets (vectors) of current-voltage drops values and images of cross-sections of the barrier corresponding to these sets. Fig. 3 shows the earth model of a part of an embankment with the Electrical Impedance Tomography (EIT) system, which includes: electrode system, electronic voltage distribution module for individual electrodes and a module for recording results. The glass panes of the terrarium made it possible to observe the changes taking place in the mass of the earth embankment caused by seepage. Thanks to the possibility of observing the interior of the earth dam, it was possible to gather a large set of data containing vectors of electrical parameters and images assigned to these vectors.



Fig. 3. The physical model of the Żelazny Most reservoir dam

In the dam model, 16 electrodes were placed to cover the entire embankment width. As a result, by placing rows of electrodes spaced apart at equal distances, the entire length of the barrier can be covered with the EIT system. The arrangement of the rows of electrodes in the dam is presented in Fig. 4.



Fig. 4. Scheme of the flood embankment with the electrodes placed on it

### 3.2. The concept of the neural system

The neural system of tomographic image reconstruction is the original concept of a system that contains many neural networks. When run in parallel, they generate an image consisting of single points. Each of the output image points is the effect of an independent, separately trained neural network. By using this method, two-dimensional (2D) and three-dimensional (3D) images are generated. From the point of view of the mechanism of creating the output image, the difference between 2D and 3D images depends on the number of pixels that make up a single image. In the case of 3D images, these points are vastly more numerous than in the case of 2D images.

As mentioned before, the EIT system that was touched upon consisted of a set of 16 electrodes, which generated 208 voltage drops during each measurement. The measurements read thanks to the electrodes placed in the body of embankment, made it possible to determine the conductivity of the tested object, which is variable depending on such factors as e.g. moisture level, heterogeneity of the structure or the type of soil. The illustrated cross-section of the embankment has been divided into a grid of pixels generated as triangular elements by means of the finite element method. In the case of 2D imaging, the pixel grid of the initial image counted 2012 points, while in the case of a three-dimensional image a spatial grid of 17869 points was used. The first case is presented in Fig. 5. In the upper part of the drawing, the locations of the electrodes are marked. The 3D case is presented in Fig. 6. The density of the grid points around the electrodes serves to more accurately reflect the changes taking place inside the depicted flood bank.

Fig. 7 and 8 present the method of operation of a neural system that converts electrical signals from electrodes into 2D and 3D images. The input vector contains 208 measuring cases (1). Each single measurement case corresponds to a certain amount of voltage drop for a given pair of electrodes.

$$U = \left[\alpha_{1}, \alpha_{2}, \alpha_{3}, \dots, \alpha_{208}\right]^{T}$$
(1)

The U vector is the input vector for all artificial neural networks (ANN) included in the neural system.

The design of the neural model was based on the following assumptions:



Fig. 5. Grid of the output 2D image of the flood barrier section (counting 2012 points)



Fig. 6. Grid of the output 3D image of the flood barrier section (counting 17869 points)



Fig. 7. A mathematical neural model for converting electrical signals into 2D images



Fig. 8. A mathematical neural model for converting electrical signals into 3D images

- Each point of the output image is generated by a separate artificial neural network with 208 voltage drop values. The output of each of the neural networks is a single real number corresponding to the conductivity value of a single element of the reconstructed image (in the visual form represented by the appropriate color of the assumed scale of conductivity).
- 2. A mutual relationship between individual points of the output image is assumed. Therefore, any neural network that generates the value of a single image element can be trained independently, with randomly generated initial weights and biases.
- 3. Neural networks assigned to elements of the output image can solve both classification and regression problems. In the case of a classification issue, the generated image may be

monochrome or have several colors / shades. Then the classifier assigns a given pixel to a specific color. If the network implements the regression problem, the output generates a real number, corresponding to the conductivity value of the given element. This type of imaging is the most desirable, but this network layout is the most difficult to train. Neural systems described in this paper deal with regression issues.

During the research, many trials were carried out, taking into account various configurations of the neural multi-layered perceptron. In particular, variants were analyzed taking into account changes in the following factors affecting the efficiency of the neural system: selection of network training algorithm, number of hidden layers and number of neurons in each layer of the network, parameters of the perceptron (learning factor, maximum number of incorrect validations, momentum and others). The possibility of using new solutions in the field of convolutional neural networks (CNN) was also analyzed. The research results showed that CNN networks are ineffective in this case due to insufficient data input - especially in comparison to the high resolution of the output image.

Due to the large amount of data and the need to train several thousand neural networks (for the 3D model), the implementation of the above concept required the use of fast algorithms including parallel computations and computers with high computing power.

# 3.3. Training process of the selected neural network

The analysis of the training process for the selected neural network included in the neural system for the reconstruction of the 2D image is presented below. In this case, the complete neural system counted 2012 separately trained

ANNs. Due to the large number of networks, in this study it is impossible to present the learning process of all artificial neural networks.

Fig. 9 presents a diagram of the used model of the neural network. The network has 208 inputs, 10 neurons in the hidden layer and 1 neuron in the output layer. The hidden layer uses a logistic transfer function. In the output layer, the transfer function is linear.

Table 1 presents the results of training one neural network, selected randomly from the system integrating 2012 networks. Presented network generates on the output a single pixel of the output image. The total number of cases used in the network training process was 10442. All cases were randomly divided into 3 sets: training, validation and



Fig. 9. A neural network model that generates a single point of the output image

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Division of the data set	The number of cases in a given set	Mean Squared Error (MSE)	Regression (R)
Learning set (70%)	7310	1.35760·10 <sup>-3</sup>	0.997303
Validation set (15%)	1566	5.84343·10 <sup>-3</sup>	0.988642
Test set (15%)	1566	6.88341·10 <sup>-3</sup>	0.987701

Table 1. The division of data into sets and results of the training process

test in the following proportions: 70%, 15%, 15%. The validation set was used to determine the moment of stopping the training process. It is used to verify the quality of the obtained network. The training process ends when the gradient change dynamics approaches zero.

The Mean Squared Error (MSE) reflects the mean square difference between the outputs and the reference values. The lower the MSE values, the better. Zero MSE means no error. The training set was burdened with the lowest learning error, which is the most common and correct situation. The low MSE error of the training set results from the fact that the weight of the network is best adapted to the training cases. The highest medium-squared error (MSE) of  $6.88341 \cdot 10^{-3}$  occurred with reference to the test set. A slightly smaller MSE error of  $5.84343 \cdot 10^{-3}$  was recorded for the validation set. The smallest error was noted in relation to the training set.

Another analyzed network quality indicator was the regression of R. R = 1 means full compliance of the outputs with the patterns, while R = 0 means the lack of connections between them. The regression coefficient merit for all three sets was very high, close to 1. This proves the high ability of the network to knowledge generalization (that is, the correct conversion of input data to output information not only for the training set).

The results obtained as a result of checking the network on the test set are the most reliable indicator of the effectiveness of a given network, because cases from this set do not participate in the learn-



Fig. 10. Correlation diagrams of a neural network

ing process. Good MSE and R indices for the test and validation test indicate lack of over-training.

Fig. 10 presents correlation diagrams of the considered network. As you can see the difference beyond the reference lines is noticeable, however the number of cases away from the reference line is not large. This is evidenced by the overlapping correlation lines for all considered sets: the training, vali-

dation and test sets, and collectively (for all three sets).

Fig. 11 presents the mean square error (MSE) diagrams recorded during the network training process. MSE values are low. The relatively regular shape of the lines (no large fluctuations) indicates the



Fig. 11. MSE error charts for the training, validation and test sets

lack of overfitting and thus the high efficiency of the developed system of tomographic reconstruction of the image. The hyperbolic shape of the curves indicates a sufficient number of training cases. The chart marks the thirtieth epoch (iteration) on which the learning of the network was completed. This is the iteration in which the MSE error of the validation set has reached its minimum.

Fig. 12 presents a histogram of errors (differences) between the values generated by the network and the patterns. Each vertical bar indicates the number of deviations from the reference value. As you can see, the largest number of deviations are very small errors, with values close to zero. The shape of the histogram is similar to the normal distribution curve. This fact also confirms the high quality of the received solution.

# 4. Results of research on the neural system of reconstructing tomographic images

As part of the research work, two neural models of tomographic image reconstruction systems have been developed. The first model realized the issues of flat (2D) imaging, while the second model generated spatial (3D) images. This chapter presents the effects of both neural network systems.

In Table 2a in two columns, the patterns and reconstructed images generated by the 2D controller are summarized. Table 2b presents a graphical representation of differences in the values of individual pixels between the reference images and reconstructed images presented in



Fig. 12. Histogram of network error learning process

Table 2a. Results of 2D imaging



Table 2b. Differences in 2D imaging results



Table 2a. The color scale in the illustrations in Table 2b reflects differences in the conductivity between the elements of the reference images and the elements of the reconstructed images.

In Table 3a, the patterns and reconstructed images generated by the 3D controller are compared in a similar way. Table 3b presents a graphical representation of differences in the values of individual pixels between spatial model images and reconstructed images presented in Table 3a.

As in Table 2b, the color scale in the illustrations in Table 3b reflects differences in conductivity between the elements of the reference images and the elements of the reconstructed images. When analyzing table 2a, it can be seen that the resulting images accurately represent the shapes and colors of the reference images. In the case of the 2D model, the numerical values of the pixels of the reference image were real numbers belonging to the range from 1 to 3. From Table 2b, the values of errors of images reconstructed with respect to their patterns can be read. You can see that most pixels on the grid do not contain errors (no color). In the case of deviations greater than zero, most errors do not exceed 0.2.

Table 3a presents a comparative analysis of reconstructed 3D images. High accuracy of mappings for all five presented cases is also visible here. The spatial grid of the 3D model has as many as 17869 points. The numerical values of the pixels of the reference image were real numbers that belong to the range from 1 to 2. Table 3b shows the values of errors of images reconstructed with respect to their patterns. Most pixels on the grid do not contain errors (no color). As in the 2D model, non-zero deviations in most cases do not exceed 0.2.

### 5. Conclusion

The article presents the original concept of a neural system for the reconstruction of tomographic images. The effectiveness of the method has been verified based on the conditions of the "Żelazny Most" Flotation Wastes Depository. Taking into account the key structural features of the Żelazny Most technical facility, a physical model of the flood embankment part was developed. The above model was equipped with an electrode system and the necessary tomography devices (EIT), which enabled the execution of many measurements of electrical quantities and the allocation of cross-sections of the investigated embankment model to those sizes. The data obtained in this way was used to train the neural network system. An innovative feature of the solution is the separate training of a large number of neural networks in the amount corresponding to the resolution of the reconstructed image mesh.

During the laboratory experiments two models of reconstruction of tomographic images were developed - flat (2D) and spatial (3D). The obtained results indicate that the presented method of neural imaging can be effective both in the case of two- and three-dimensional reconstruction. The application of a system of many separate neural networks operating simultaneously to depict the cross-section of the embankment damage enabled the generation of exact mappings of the given patterns. The quality of these mappings is sufficient to correctly identify the nature of threats, as well as to assess the rate of changes taking place inside the flood embankment.

Taking into account the possibility of taking measurements at regular intervals, the rate of leakage spreading can be easily determined. The above information enables not only a accurate diagnosis useful for determining the embankment's reliability level, but also an effective forecast of the moment of the coming disaster. Thanks to information obtained by the use of neural imaging system, it is possible to appropriately plan actions to prevent damage to flood protection facilities.

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The cross-sectional patterns of the flood The images reconstructed by using a ID embankment neural generator 1 2 3 4 5

# Table 3a. 3D imaging results





# References

- 1. Adedigba S A, Khan F, Yang M. Dynamic failure analysis of process systems using neural networks. Process Safety and Environmental Protection 2017; 111: 529-543, https://doi.org/10.1016/j.psep.2017.08.005.
- Banasiak R, Wajman R, Sankowski D, Soleimani M. Three-Dimensional Nonlinear Inversion of Electrical Capacitance Tomography Data Using a Complete Sensor Model. Progress In Electromagnetics Research (PIER) 2010; 100: 219-234, https://doi.org/10.2528/ PIER09111201.
- 3. Beckers B, Schütt B. The elaborate floodwater harvesting system of ancient Resafa in Syria–Construction and reliability. Journal of arid environments 2013; 96: 31-47, https://doi.org/10.1016/j.jaridenv.2013.04.004.
- 4. Bouzelha K, Hammoum H, Amirouche C, Chaouadi T. Reliability analysis of stability to sliding of earthen embankment under seismic effect. Procedia Structural Integrity 2017; 5: 77-84, https://doi.org/10.1016/j.prostr.2017.07.070.
- 5. Curt C, Talon A. Assessment and control of the quality of data used during dam reviews by using expert knowledge and the ELECTRE TRI method. Journal of Computing in Civil Engineering 2011; 27.1: 10-17, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000187.
- 6. Gamse S, Zhou W H, Tan F, Yuen K V, Oberguggenberger M. Hydrostatic-season-time model updating using Bayesian model class selection. Reliability Engineering & System Safety 2018; 169: 40-50, https://doi.org/10.1016/j.ress.2017.07.018.
- 7. Gottardi G, Gragnano C G, Rocchi I, Bittelli M. Assessing River Embankment Stability Under Transient Seepage Conditions. Procedia Engineering 2016; 158: 350-355; https://doi.org/10.1016/j.proeng.2016.08.454.
- 8. Hawryluk M, Mrzygłód B. A durability analysis of forging tools for different operating conditions with application of a decision support system based on artificial neural networks (ANN). Eksploatacja i Niezawodnosc Maintenance and Reliability 2017; 19 (3): 338–348, https://doi.org/10.17531/ein.2017.3.4.
- 9. Ji J, Chan C L. Long embankment failure accounting for longitudinal spatial variation-A probabilistic study. Computers and Geotechnics 2014; 61: 50-56, https://doi.org/10.1016/j.compgeo.2014.05.001.
- Kłosowski G, Kozłowski E, Gola A. Integer linear programming in optimization of waste after cutting in the furniture manufacturing. Advances in Intelligent Systems and Computing 2018; 637: 260-270, https://doi.org/10.1007/978-3-319-64465-3\_26.
- 11. Kozłowski E, Kowalska B, Kowalski D, Mazurkiewicz D. Water demand forecasting by trend and harmonic analysis. Archives of Civil and Mechanical Engineering 2018; 18(1): 140-148, https://doi.org/10.1016/j.acme.2017.05.006.
- 12. Kryszyn J, Smolik W, Radzik B, Olszewski T, Szabatin R. Switchless Charge-Discharge Circuit for Electrical Capacitance Tomography. Measurement Science and Technology 2014; 25(11): 115009, https://doi.org/10.1088/0957-0233/25/11/115009.
- Low B K. FORM, SORM, and spatial modeling in geotechnical engineering. Structural Safety 2014; 49: 56-64, https://doi.org/10.1016/j. strusafe.2013.08.008.
- 14. Mazurkiewicz D. Maintenance of belt conveyors using an expert system based on fuzzy logic. Archives of Civil and Mechanical Engineering, 2015; 15.2: 412-418, https://doi.org/10.1016/j.acme.2014.12.009.
- 15. Nishimura S, Shimizu H. Reliability-based design of ground improvement for liquefaction mitigation. Structural Safety 2008; 30.3: 200-216, https://doi.org/10.1016/j.strusafe.2006.11.002.
- 16. Prajapati A, Ganesan S. Application of Statistical Techniques and Neural Networks in Condition-Based Maintenance. Quality and Reliability Engineering International 2013; 29(3): 439-461, https://doi.org/10.1002/qre.1392.
- 17. Rusek J. Application of Support Vector Machine in the analysis of the technical state of development in the LGOM mining area. Eksploatacja i Niezawodnosc Maintenance and Reliability 2017; 19 (1): 54–61, https://doi.org/10.17531/ein.2017.1.8.
- Rymarczyk T, Tchórzewski P, Adamkiewicz P, Duda K, Szumowski J, Sikora J. Practical Implementation of Electrical Tomography in a Distributed System to Examine the Condition of Objects. IEEE Sensors Journal 2017; 17(24): 8166-8186, https://doi.org/10.1109/ JSEN.2017.2746748.
- 19. Rymarczyk T. New Methods to Determine Moisture Areas by Electrical Impedance Tomography. International Journal of Applied Electromagnetics and Mechanics 2016; 52:79-87, https://doi.org/10.3233/JAE-162071.
- 20. Stefanek P, Romaniuk D. Zastosowanie monitoringu geotechnicznego i środowiskowego na obiekcie unieszkodliwiania odpadów wydobywczych Żelazny Most. Inżynieria Morska i Geotechnika; 2015, 3: 376--381.
- 21. Stefanek P, Serwicki A. Ograniczenie oddziaływania OUOW Żelazny Most na środowisko poprzez zmianę technologii składowania odpadów. Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie; 2014, 6: 36--42.
- 22. Ung S T, Williams V, Bonsall S, Wang J. Test case based risk predictions using artificial neural network. Journal of Safety Research 2006; 37.3: 245-260, https://doi.org/10.1016/j.jsr.2006.02.002.
- Wu Z Y, Li Y L, Chen J K, Zhang H, Pei L. A reliability-based approach to evaluating the stability of high rockfill dams using a nonlinear shear strength criterion. Computers and Geotechnics 2013; 51: 42-49, https://doi.org/10.1016/j.compgeo.2013.01.005.
- 24. Yajun W, Wohua Z, Weiliang J, Changyu W, Dachun R. Fuzzy stochastic generalized reliability studies on embankment systems based on first-order approximation theorem. Water Science and Engineering 2008; 1.4: 36-47.
- 25. Zagrożenia okresowe występujące w Polsce, Wydział Analiz Rządowego Centrum Bezpieczeństwa, styczeń 2013.
- Zuber N, Bajrić R. Application of artificial neural networks and principal component analysis on vibration signals for automated fault classification of roller element bearings. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2016; 18 (2): 299–306, https://doi. org/10.17531/ein.2016.2.19.

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# CONCENTRATION ANALYSIS OF GASES FORMED IN MINERAL OIL, NATURAL ESTER, AND SYNTHETIC ESTER BY DISCHARGES OF HIGH ENERGY

# ANALIZA STĘŻEŃ GAZÓW POWSTAJĄCYCH NA SKUTEK ODDZIAŁYWANIA ŁUKU ELEKTRYCZNEGO NA OLEJ MINERALNY ORAZ ESTRY NATURALNE I SYNTETYCZNY\*

The paper describes physical foundations of gases generation in different electroinsulating liquids. The authors reviewed literature concerning the analysis of gases generated in these liquids as a result of discharges of low energy. The main purpose of the research was to compare gases formed in mineral oil, natural ester, and synthetic ester resulting from discharges of high energy, which has not been studied so far. The comparison was done both in terms of gases composition and their concentration. The purpose of the research was to give an answer to the question: which of the analysed liquids ensure higher operation safety if there is a discharge of high energy in the insulating system.

*Keywords*: transformer, diagnostics, mineral oil, natural ester, synthetic ester, electric arc, discharge of high energy, gases, gas chromatography.

W pracy opisano podstawy fizyczne związane z powstawaniem gazów w różnych cieczach elektroizolacyjnych. Dokonano przeglądu literatury dotyczącego analizy gazów generowanych w tych cieczach w wyniku wyładowań zupelnych. Głównym celem badań było porównanie gazów powstających w oleju mineralnym, estrze naturalnym oraz estrze syntetycznym w wyniku oddziaływania na te ciecze wyładowań zupelnych o bardzo dużej energii, co dotychczas nie było przedmiotem badań. Porównania dokonano zarówno pod kątem składu gazów jak i ich stężenia. Wyniki badań miały przede wszystkim dać odpowiedź na pytanie: która z analizowanych cieczy charakteryzuje się większym bezpieczeństwem eksploatacji w sytuacji wystąpienia w układzie izolacyjnym wysokoenergetycznego wyładowania zupełnego.

*Slowa kluczowe*: transformator, diagnostyka, olej mineralny, ester naturalny, ester syntetyczny, łuk elektryczny, wyładowania zupełne, gazy, chromatografia gazowa.

# 1. Introduction

Mineral oil is the most frequently applied liquid in power devices. However, for the last 20 years we have been observing interest increase of alternative liquids, including synthetic esters and natural esters [1, 10]. These liquids, in comparison to mineral oil, have properties which are considered as their advantages. These properties are, first of all, ecological values (biodegradability, non-toxicity), operation safety linked with a high flash point and fire point [1, 2, 4, 13, 14], and also high water solubility [1, 19, 20].

Fire safety is one of most important problems faced by manufacturers and users of electrical power devices. It refers mainly to devices filled with electroinsulating liquids used in urban areas and densely populated. The companies which deal with insuring electropower devices are more and more aware of the fire risk involved with application of different kinds of electroinsulating liquids. Thus, they required the information about fire-hazard specificity of an applied liquid [1-3, 16, 18].

Synthetic esters are used mainly in distribution transformers and transformers installed at places whose fire safety and environment protection issues are the most important. They are used more and more often in grid transformers and special transformers which work in traction, high-speed trains, and wind farms. Synthetic esters are commonly applied when high temperature of device operation is expected, often in connection with resistant to high temperature solid insulation, e.g. aramid paper. The first grid transformers filled with synthetic esters were installed in Europe in 2003 [1, 10].

Natural esters are commonly used in the USA to replace mineral oil in distribution transformers of up to 60 kV. In Europe, the first commercial application of natural esters in transformers took place in the late 1990s [1, 21].

Electroinsulating liquids, alternative to mineral oil, such as synthetic ester and natural ester are chosen by operators more and more often but still with substantial wariness. It results from the fact that, opposite to mineral oil, properties of these liquids are not well-known yet. One of the most essential properties involving transformer operation safety are gas properties of the liquid. A few scientific centres in the world are doing research on an analysis of gasses generated in alternative electroinsulating liquids when there are discharges of low energy and also overheating in the insulating system. These research are targeted at pointing gases which are characteristic for a given type of defect and at determining values of typical concentrations of particular gases. These investigations are necessary to conduct Dissolved Gas Analysis (DGA) for transformers insulated with the new electroinsulating liquids. We should note here that the DGA method is considered as the one of the most important diagnostic method of the power transformers.

# 2. Physical foundations of gases generation in electroinsulating liquids

Mineral oils are a mixture of naphthenic hydrocarbons  $(C_nH_{2n}, C_nH_{2n-2})$ , paraffin hydrocarbons  $(C_nH_{2n+2})$ , and aromatic hydrocarbons  $(C_nH_n)$ . In their structure they have groups of CH, CH<sub>2</sub>, and CH<sub>3</sub> linked together by carbon-carbon bonds. Breaking the C-C or C-H bonds can be caused by electrical or thermal faults. It results in appearing small (among many other more complex forms) unstable fragments in radical or ionic form  $(H^{\bullet}, CH3^{\bullet}, CH2^{\bullet}, CH^{\bullet}, C^{\bullet})$  which violently recombine into molecules such as hydrogen or hydrocarbons with one, two, three or four atoms of carbon. Also, solid particles of carbons and hydrocarbon polymers are generated. The gases dissolve in the electroinsulating liquid or concentrate in the space over the liquid if they are generated violently and in a very large amount [17].

The reasons of natural and synthetic ester decomposition, as in the case of mineral oil, are electrical and thermal faults. A large number of ester groups and chains (from 16 to 18 carbons) in connection with the lack of naphthenic and aromatic structures, which occur in mineral oil, makes the composition of esters substantially different. Although the gases generated by electrical and thermal faults are the same for mineral oil and esters, we should point out a considerable difference in the amount of the generated gases and different solubility of these gases in electroinsulating liquids. The example here can be carbon monoxide and dioxide, which are generated in large quantities in the case of thermal exposure of esters [9, 10, 22].

Like in the case of mineral oil, the main reasons of ester decomposition is breaking the carbon-hydrogen and carbon-carbon bonds. This way, free radicals of hydrogen and hydrocarbon radicals are generated. They can bind to other molecules, generating in this way hydrogen, methane, ethane, propane, butane. Further decomposition can lead to forming such products as: ethylene, acetylene, propylene, or in extreme cases – carbon particles.

During discharges of low energy, such as partial discharges, the weakest C-H bonds are broken (338kJ/mole), which is caused by the ionisation effect. Much higher energy is necessary for the scission of single bonds C-C (607 kJ/mole), double bonds C=C (720 kJ/mole) or triple bonds C=C (960 kJ/mole) [16, 17].

It results from the literature that the characteristic gases which are generated in mineral oil as a result of discharge of high energy are  $C_2H_2$ ,  $H_2$ ,  $CH_4$ ,  $C_2H_4$ , where acetylene is considered as the key gas [6, 11, 16, 17].

Generation of acetylene requires the temperature of at least 800°C, and its rapid quenching to lower temperatures, which enables the stability of this gas. Acetylene is thus formed in significant quantities mainly in arcs, where the conductive ionized channel is at several thousand of degrees Celsius, and the interface with the surrounding oil is necessarily below 400°C. This gas can also be generated at the temperature below 800°C, but in much smaller amounts. At the temperature within the range from 500°C to 800°C, we can observe formation of carbon molecules. This effect takes place mainly when the arc occurs or the oil is locally overheated [17].

As it was mentioned before, the main reasons of gas generation, both for mineral oil and esters is breaking carbon-hydrogen and carbon-carbon bonds. Therefore, the gases which are generated as a result of decomposition of these liquids are mainly hydrogen and hydrocarbons. Due to the chemical composition of oil and esters, we should expect significant differences in the amount of the generated gases.

# 3. Qualitative and quantitative analysis of gases generated in electroinsulating liquids - literature review

According to standard IEC 60599 [17], electric defects which occur in the insulating system can be divided into partial discharges, discharges of low energy and discharges of high energy. Below is a review of literature concentrating on the analysis of gases generated as a result of discharges of low energy in different electroinsulating liquids.

I. U-Khan, Z. Wang, I. Cotton, and S. Northcote presented in [23] results of DGA investigations for electroinsulating liquids exposed to the discharges of low energy. The research was done in the point-toplate electrodes configuration with the interelectrode gap of 15 mm. In order to provide a sufficiently high concentration of the gases, they led to twenty breakdowns in each of the investigated liquids. After the breakdown, voltage was immediately switched off using an overcurrent relay, whose value was set for 3 A on the primary winding of the test transformer. The duration of discharge was in the range from 20 to 100 ms. Samples for the experiments were taken by means of a valve placed in the bottom of a tight vessel. According to the authors of [23], when we can provide a sufficiently long time between the breakdown and taking the sample, we can expect a uniform distribution of the gases in the whole volume of the liquid. Unfortunately, the authors did not reveal the value of this time. Table 1 presents their research results.

 Table 1. Research results obtained by the authors of [23] concerning exposure of different electroinsulating liquids to discharges of low energy

LIQUID	GAS CONCENTRATION, ppm						
Пібоїр	MINERAL OIL		NATURAL ESTER		SYNTHETIC ESTER		
GAS	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER	
H <sub>2</sub>	5	901	8	191	7	97	
$CH_4$	1	145	1	14	0	9	
$C_2H_6$	0	24	2	10	0	2	
$C_2H_4$	1	270	1	63	1	26	
$C_2H_2$	1	1540	6	280	0	126	
СО	18	6	6	51	9	37	
TDCG	26	2886	24	609	17	297	

On the basis of the conducted experiments concerning exposure of electroinsulating liquids to discharges of low energy, the authors of [23] pointed out that acetylene is one of the key gases generated in the case of all the investigated liquids. All the investigated samples were characteristic of a high concentration of this gas. Despite the same exposure of the liquids, they found from 5 to 10 times greater acetylene concentration in mineral oil than for esters. The authors of [23] also found high concentration of hydrogen and ethylene for the liquids exposed to discharges of low energy. They also pointed out less intense generation of combustible gases in esters, in comparison to mineral oil. According to the authors of this work, this can make identification of defects more difficult.

M. Jovalekic, D. Vukovic, and S. Tenbohlen presented in [12] research results of the influence of discharges of low energy on gas generation in different electroinsulating liquids. The investigated liquids underwent 90 lightning impulses  $(1.2/50 \,\mu s)$  in the point-to-point configuration (interelectrode gap equal to 4 mm) in a tightly closed vessel of the volume of 1618 ml. Next, each of the liquids was stirred so as to obtain a uniform gas distribution in its whole volume. At the next step, a sample was taken and the chromatographic analysis was done. The results are presented in Table 2.

LIQUID	GAS CONCENTRATION, ppm						
GAS	MINERAL OIL	NATURAL ESTER	SYNTHETIC ESTER				
H <sub>2</sub>	1775	605	558				
CH <sub>4</sub>	155	99	120				
C <sub>2</sub> H <sub>6</sub>	<1	<1	<1				
C <sub>2</sub> H <sub>4</sub>	214	229	118				
C <sub>2</sub> H <sub>2</sub>	2100	953	915				
СО	<1	155	308				
TDCG	4244	2041	2019				

 Table 2. Research results obtained by the authors of [12] concerning exposure of different electroinsulating liquids to discharges of low energy

Impulse voltage was equal to 134 kV, which meant energy in capacitors equal to 409.6 J (four-stage generator). However, only from 0.1 to 1% of this energy was used in liquid decomposition process. Most of the energy was converted into heat in the damping resistor of the generator.

On the basis of the obtained results, the authors of [12] found that the key gases generated at this type of defect are hydrogen and acetylene. For esters, they also found the presence of carbon monoxide, as opposite to mineral oil, where this gas was not found.

R. Eberhardt et al in [5] also analysed the influence of discharge of low energy on gas generation in mineral oil, natural ester, and synthetic ester. The investigations were done in a vessel of the volume of 17 litres in the plate-to-U-shape electrode. There was pressboard placed between the electrodes. Alternating voltage was raised in such a way that the discharge appeared after about 20 seconds. Each sample underwent the electric breakdown ten times. The authors found that acetylene is the key gas at this type of defect. Its largest increase was found for natural ester. The increase of acetylene concentration in mineral oil and synthetic ester was similar. They found a considerable difference in gas generation between natural ester and synthetic ester. For natural ester, they proved the presence of acetylene and ethane. They also concluded that there is no increased generation of carbon monoxide and dioxide for both natural and synthetic ester.

C. Perrier, M. Marugan, M. Saravolac, and A. Beroual proved in [15] that when mineral oil and esters are exposed to discharges of low energy then mainly hydrogen and acetylene are generated.

Summing up the presented above literature review, we can conclude that in the research conducted up to now, the authors have concentrated mainly on the analysis of gases generated as a result of short duration discharges of low energy. The authors of this article conducted experiments of exposing the liquids to the discharge in the form of the electric arc of very high energy, reaching 5 kJ. The conditions of these experiments and their results are presented in the subsequent chapter.

# 4. Investigations of gases generated in electroinsulating liquids by discharge of high energy

# 4.1. The aim of the study

The aim of the research was to compare gases generated in mineral oil, natural ester (manufactured on the basis of soybean oil), and synthetic ester by discharge of high energy. The comparison was done both in terms of gas composition and their concentration. The purpose of the study was to give an answer to the question: which of the analysed liquids ensure higher operation safety if there is a discharge of high energy in the insulating system.

Resulting from the discharge of high energy, very large quantities of gases were generated in the liquids in the form of bubbles, which migrated to the headspace. The quantity of the generated gases was so large that it caused significant pressure changes in the chamber. Due to a short discharge time (5, 10, or 15 s) and taking the samples immediately after the arc extinction, only a slight amount of the generated gas was able to dissolve in the liquid. That is why the authors analysed the gas mixture taken from the headspace.

## 4.2. System for gas generating and research procedure

For exposing the investigated liquids to discharge of high energy, the authors used a hermetic chamber which had been used before for investigations of the dielectric response of pressboard samples [7, 8]. The chamber was rebuilt for the needs of this experiment (Fig. 1). The walls of this chamber were made of a glass pipe, whereas the base and the lid were discs made of organic glass. All screw connections were made as gas tight using oil resistant seals of the O-ring type. After assembling the chamber, a tightness test was done using compressed air. No pressure drop was found in the whole system (within forecast pressure ranges which could occur during the experiment), thus the system was considered as gas tight.



Fig. 1. Sketch of the chamber for exposing the insulating liquids to discharge of high energy

The volume of the chamber was  $1800 \text{ cm}^3$ , after including the volume of the electrode (which was  $106 \text{ cm}^3$ ) the authors determined the volume of the liquid in the chamber. The height of the liquid column in the chamber was 15.5 cm, thus knowing the dimensions of the chamber, it is possible to calculate the oil volume. The calculated oil volume was equal to  $1360 \text{ cm}^3$ . The volume of the air remaining in the chamber (the volume of headspace) was thus equal to  $334 \text{ cm}^3$ .

The electric arc was generated in the point-to-plate electrodes configuration. The gap between the electrode was 3 mm. The point electrode was connected to a source of high voltage, whereas the plate electrode was grounded. A special point electrode was designed to allow investigating pressure changes in the chamber and taking gas samples from headspace without any contact with atmospheric air. The electrode was made in the form of a brass pipe (of external diameter 3 mm and internal diameter 2 mm) ending with a copper cone on one side. The pipe, in the part which was above the liquid level had a gas extraction hole of the diameter of 1 mm. The other end of the point electrode was connected by means of dielectric pipes made of PCV with a three-way valve. The valve allowed connecting the system with the pressure meter or a gas tight syringe used for taking gas from headspace.

Voltage was supplied to the chamber by means of the system presented in Figure 2. An autotransformer (AT1) was applied in the voltage regulation system, current and voltage in the autotransformer circuit were measured. The voltage supplied from the autotransformer was raised using a high voltage transformer (TR1) of the ratio of 110000/220. On the HV side, voltage was measured using electrostatic kilovoltmeters, and current by means of a milliammeter. For reducing discharge current, the authors used a non-linear damping resistor R1.

After arc ignition in the chamber (arc ignition took place at 25 kV for mineral oil, 24 kV for synthetic ester, and 25 kV for natural ester), voltage values on upper windings of AT1 and TR1 decreased. Voltage and current of arc for all liquids were similar and they were 2.5 kV and 140 mA, respectively.

The arc current corresponds to the value of the current measured on the low side of the transformer TR1, which was 70 A during arc ignition (the TR1 ratio is 500, thus current transforming took place according to transformer ratio: 70 A/500 = 140 mA). Therefore, the power which was released on the arc was 2.5 kV  $\cdot$  0.14 A = 350 W, which corresponds to the released energy: 1750, 3500, and 5250 J, respectively for the duration of arc 5, 10, and 15 s.



Fig. 2. Scheme of the high voltage test system

All the investigated liquids were exposed to electric arc for 5, 10, and 15 s. The procedure of exposing the liquid to the electric arc was proceeded as follows:

- liquid conditioning in the air of atmospheric pressure to obtain relative saturation of the liquid equal to 40%, 4.5 litre of each investigated liquid was prepared,
- filling the chamber with the investigated liquid: the volume of the liquid was 1360 cm<sup>3</sup>,
- sealing the chamber by tightening all screw connections,
- connecting the pressure meter,
- connecting the supply and grounding wires to the suitable electrodes,
- setting the three-way valve in a position which allows pressure measurement,
- raising voltage until the moment of arc ignition,
- keeping the arc for 5 s,
- leaving the chamber for 1 minute to let the gas bubbles generated in the liquid migrate to the headspace,
- measurement of headspace pressure,
- suitable setting the three-way valve and taking 12 ml of the gas for the chromatographic analysis.

Then for each of the liquids the above presented activities were repeated twice (excluding first activity) increasing every time the duration of arc by 5 s.

The authors used a gas chromatograph type 8610C TOGA supplied by SRI Instruments for the analysis of generated gases. The chromatograph is equipped with two detectors: the flame ionisation detector FID and the thermal conductivity detector TCD. By means of the FID we can subsequently detect the following gases: carbon monoxide, methane, carbon dioxide, ethylene, ethane, acetylene, propane, propylene, whereas by means of the TCD we can detect subsequently: hydrogen, oxygen, and nitrogen.

### 4.3. Research results and conclusions

Table 3 and Figures from 3 to 15 present results of a qualitative and quantitative analysis of the gases generated in mineral oil, natural ester, and synthetic ester during discharge of the time of 5, 10, and 15 s.

In order to measure the pressure of headspace a manometer was used. Table 4 and Figure 16 present results of these investigations.

Table 3. The concentration of gases generated in mineral oil, natural ester, and synthetic ester during discharge of the time of 5, 10, 15 s; area – area of the peak (on the gas chromatogram) which is proportional to butane concentration, TCG – Total Combustible Gas

LIQUID GAS	MINERAL OIL			NATUTAL ESTER			SYNTHETIC ESTER		
	5 s	10 s	15 s	5 s	10 s	15 s	5 s	10 s	15 s
H <sub>2</sub> , %	6.228	8.671	12.82	3.143	4.047	7.087	2.605	5.213	7.065
<b>0</b> <sub>2</sub> , %	17.30	16.73	15.06	18.22	17.883	17.12	18.33	17.61	17.40
N <sub>2</sub> , %	73.25	70.96	63.41	74.30	75.39	72.55	75.72	73.74	72.06
<b>CO</b> , %	0.0409	0.0204	0.0380	0.6576	0.8518	1.402	1.043	2.114	2.886
CH <sub>4</sub> , %	0.3111	0.4609	0.7092	0.0436	0.0505	0.0943	0.0386	0.0871	0.1190
CO <sub>2</sub> , %	0.0694	0.1175	0.0483	0.1017	0.1078	0.1270	0.0825	0.0990	0.1223
С <sub>2</sub> Н <sub>4</sub> , %	0.2827	0.3789	0.5804	0.0578	0.0721	0.1315	0.0474	0.1103	0.1501
С <sub>2</sub> Н <sub>6</sub> , %	0.0055	0.0086	0.0133	0.0006	0.0009	0.0010	0.0008	0.0018	0.0024
С <sub>2</sub> Н <sub>2</sub> , %	2.816	3.763	5.678	1.395	1.769	2.957	0.9189	1.970	2.724
С <sub>3</sub> Н <sub>8</sub> , %	0.0003	0.0004	0.0006	-	-	-	-	-	0.0002
С <sub>3</sub> Н <sub>6</sub> , %	0.0260	0.0376	0.0575	0.0021	0.0021	0.0034	0.0020	0.0049	0.0064
C <sub>4</sub> H <sub>10</sub> , area	32.90	48.30	71.40	6.10	7.10	10.90	4.24	7.70	14.64
<b>TCG</b> , %	9.7105	13.3408	19.897	5.2997	6.7934	11.6762	4.6557	9.5011	12.9531

On the basis of the results presented above, the following conclusions were drawn:

- · for all tested liquids a very high concentration of hydrogen and acetylene were measured, while in the case of esters also a high concentration of carbon monoxide was found; for the experimental conditions, the concentrations of these gases exceed 1% (10.000 ppm); these gases can be used to identify a high energy discharge defect,
- the sum of combustible gases (excluding butane for which it was impossible to carry out a quantitative analysis due to the lack of this gas in the gas mixture used for calibration of the chromatograph) is about 38% higher for mineral oil than for both esters (Fig. 15) - this indicates a greater exploitation safety of esters in the case of electric arc ignition,
- · during high energy discharge the increase of headspace gas pressure for all investigated liquids was observed (Fig. 16).

A substantial concentration increase of combustible gases in the insulating system generated during electric arc leads to a very high risk of ignition of these gases. Such ignition was observed while investigating synthetic ester at the time of exposing to the discharge equal to 15 seconds. Figure 17 presents the gas concentration in headspace in the situations when gas ignition took place and it did not.

The authors found a significant difference between the composition of the gas mixture in synthetic ester in the case of the experiment with and without combustible gas ignition. In the case with no ignition, the sum of combustible gases was 12.9%, whereas in the case of ignition the concentration of these gases was merely 3.8%. Moreover, in the experiment where gas ignition took place, the authors observed



on discharge duration for mineral oil (MO). natural ester (NE), and synthetic ester (SE)

%











Fig. 6. The concentration of carbon monoxide de- Fig. 7. The concentration of methane depending on Fig. 8. The concentration of carbon dioxide on dispending on discharge duration for mineral oil (MO), natural ester (NE), and synthetic ester (SE)



Fig. 9. The concentration of ethylene depending on Fig. 10. The concentration of ethane depending on Fig. 11. The concentration of acetylene depending discharge duration for mineral oil (MO), natural ester (NE), and synthetic ester (SE)

discharge duration for mineral oil (MO). natural ester (NE), and synthetic ester (SE)

0.014

0.012

0.010

0.008

0.006

0.004

0.002

0.000

MO INE DE

5





15

charge duration for mineral oil (MO). natural ester (NE), and synthetic ester (SE)



discharge duration for mineral oil (MO), natural ester (NE), and synthetic ester (SE)

10

Duration of discharge, s

on discharge duration for mineral oil (MO), natural ester (NE), and synthetic ester (SE)



Fig. 12. The concentration of propane depending on Fig. 13. The concentration of propylene depending Fig. 14. The concentration of butane depending on discharge duration for mineral oil (MO), natural ester (NE), and synthetic ester (SE)

on discharge duration for mineral oil (MO), natural ester (NE), and synthetic ester (SE)

discharge duration for mineral oil (MO), natural ester (NE), and synthetic ester (SE)



Fig. 15. The total combustible gas content depending Fig. 16. Headspace gas pressure depending on dison discharge duration for mineral oil (MO), natural ester (NE), and synthetic ester (SE)



charge duration for mineral oil (MO), natural ester (NE), and synthetic ester (SE)

Table 4. Headspace gas pressure measured immediately after extinction of the arc for discharge duration 5, 10, and 15 s

LIQUID	MINERAL OIL			NATURAL ESTER			SYNTHETIC ESTER		
DURATION	5 s	10 s	15 s	5 s	10 s	15 s	5 s	10 s	15 s
PRESSURE, mbar	97	210	280	54	77	140	22	111	154



Fig. 17. Comparison of gas concentrations in the cases of gas ignition and no ignition; arc duration 15 s

much lower oxygen concentration and considerably higher concentration of carbon monoxide in comparison to the experiment where ignition did not occur. Gas ignition resulted in negative pressure in the measurement system at the level of 402 mbar in reference to the atmospheric pressure. In the experiment where gas ignition did not occur, the increase of pressure was found at the level of 154 mbar over the atmospheric pressure.

In all the liquids, at the moment of electric arc ignition, sudden oil degradation was observed, whose result apart from generation of combustible gases was the occurrence of carbon particles. This effect was the most noticeable for mineral oil. Figure 18 presents photographs of mineral oil colour changes during the investigation.

# 4. Conclusions

The conducted research confirmed that during the discharges of high energy in natural ester and synthetic ester, the same gases are generated as for mineral oil. These gases are: hydrogen, hydrocarbons (first of all with one, two, or three carbon atoms), carbon monoxide and dioxide. This conclusion is very important due to the diagnostics of devices insulated with these liquids. Generation of the same gases allows perform the gas analyses at the same configuration of the chromatograph.

It is important, however, that in the particular electroinsulating liquids, at the same type of defect, gases are generated of completely different concentrations, which is vital in terms of interpretation of research results obtained by means of the DGA method.

It was found a greater value of total combustible gases by about 38% in mineral oil than in both esters. This points out higher operation safety of esters in the case of arc ignition. For all the investigated liquids, the characteristic gases occurring at a very high concentration were hydrogen and acetylene, whereas for esters, the authors also found a high concentration of carbon monoxide. These


9 5

Fig. 18. The changes of mineral oil colour during the experiment: 0 s – before arc ignition, in the 3<sup>rd</sup>, 6<sup>th</sup>, 9<sup>th</sup> and 12<sup>th</sup> second of discharge duration, and in the 16<sup>th</sup> s – after the arc extinction

gases can be applied for identifying the defect which is discharge of high energy.

Most of the conclusions resulting from the conducted research are in agreement with the experiment results described in articles [12, 15, 23], by contrast they are not in agreement with the experiment results described in [5]. The authors of this work did not find excessive generation of carbon monoxide for both natural and synthetic esters.

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### References

- Cigre Brochure 436, Experience in service with new insulating liquids, 2010. 1.
- 2. Dombek G. Wykorzystanie alternatywnych cieczy elektroizolacyjnych w kontekście minimalizacji zagrożenia pożarowego transformatorów energetycznych, Przegląd Naukowo-Metodyczny. Edukacja dla Bezpieczeństwa 2016; 30(1): 857-865.
- Dombek G, Nadolny Z. Liquid kind, temperature, moisture, and ageing as an operating parameters conditioning reliability of transformer cooling 3. system. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2016; 18 (3): 413-417, https://doi.org/10.17531/ein.2016.3.13.
- Dombek G, Nadolny Z. Thermal properties of a mixture of synthetic and natural esters in terms of their application in high voltage power 4. transformers. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2017; 19 (1): 62-67, https://doi.org/10.17531/ein.2017.1.9.
- 5. Eberhardt R, Wieser B, Lick W, Muhr H M, Pukel G, Schwarz R, Baumann F. Dissolved gas analysis investigations on ester liquids after breakdown. In proc of: IEEE International Conference on Dielectric Liquids 2011, https://doi.org/10.1109/ICDL.2011.6015447.
- FIST 3-30 Transformer maintenance. US Department of the Interior Bureau of Reclamation; 2000. 6.
- Gielniak J, Graczkowski A, Gubanski S, et al. Influence of thermal ageing on dielectric response of oil-paper insulation. Materials Science-7. Poland 2009; 27(4/2): 1199-1205.
- 8. Gielniak J, Graczkowski A, Moscicka-Grzesiak H. Does the Degree of Cellulose Polymerization Affect the Dielectric Response? IEEE Transactions on Dielectrics and Electrical Insulation 2011; 18(5): 1647-1650, https://doi.org/10.1109/TDEI.2011.6032835.
- 9. Hanson D, Li K, Plascencia J, Beauchemin C, Claiborne C, Cherry D, Frimpong G, Luksich J, Lemm A, Martin R. Understanding dissolved gas analysis of ester: an updated review of gas generated in ester liquid by stray gassing, thermal decomposition and electrical discharge. In proc. of: Electrical Insulation Conference (EIC) 2016: 138-144, https://doi.org/10.1109/EIC.2016.7548611.
- IEEE Std. C57.104-1991, Guide for the interpretation of gases generated in oil immersed transformers, 1992, https://doi.org/10.1109/ 10. IEEESTD.1992.106973.
- IEEE Std. C57.155, IEEE Guide for Interpretation of Gases Generated in Natural Ester and Synthetic Ester-Immersed Transformers; 2014, 11. https://doi.org/10.1109/IEEESTD.2014.6966710.
- Jovalekic M, Vukovic D, Tenbohlen S. Dissolved gas analysis of alternative dielectric fluids under thermal and electrical stress. In proc of: 12. IEEE International Conference on Dielectric Liquids 2011, https://doi.org/10.1109/ICDL.2011.6015457.
- Longva K. Natural ester distribution transformers; improved reliability and environmental safety. Nordic Insulation Symposium 2005: 13. 293-295.
- Oommen T V. Vegetable oils for liquid filed transformers. IEEE Electrical Insulation Magazine 2002; 18(1): 6-11, https://doi. 14. org/10.1109/57.981322
- Perrier C, Marugan M, Saravolac M, Beroual A. DGA comparison between ester and mineral oils. In proc of: International Conference on 15. Dielectric Liquids 2011, ttps://doi.org/10.1109/ICDL.2011.6015411.
- Piotrowski T.DGA: od defektu do diagnozy. W materiałach V Konferencji Naukowo-Technicznej Transformatory Energetyczne i Specjalne: 16. Przyszłość i Środowisko 2004; 221-226.
- IEC 60599, Mineral oil-filled electrical equipment in service Guidance on the interpretation of dissolved and free gases analysis, 2015. 17.
- PN-EN 61100, Klasyfikacja cieczy elektroizolacyjnych według temperatury palenia i dolnej wartości opałowej, 2007. 18.

- Przybyłek P, Siodła K. Application of capacitive sensor for measuring water content in electro-insulating liquids. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2016; 18 (2): 181–185, https://doi.org/10.17531/ein.2016.2.4
- 20. Przybylek P. Water saturation limit of insulating liquids and hygroscopicity of cellulose in aspect of moisture determination in oil-paper insulation. IEEE Transactions on Dielectrics and Electrical Insulation 2016; 23(3): 1886–1893, https://doi.org/10.1109/TDEI.2016.005627.
- 21. Rapp K J, Luksich J. Application of Natural Ester Insulating Liquids in Power Transformers. In proc of: My Transfo 2014 Conference; 2014.
- 22. TJ|H2b Analytical Services, Inc., Understanding Dissolved Gas Analysis of Ester fluids-Part 2 Thermal Decomposition of Ester Fluids; 2012.
- 23. U-Khan I, Wang Z, Cotton I, Northcote S. Dissolved gas analysis of alternative fluids for power transformers. IEEE Electrical Insulation Magazine 2007; 23(5), 5–14, https://doi.org/10.1109/MEI.2007.4318269.

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### THE USE OF *PLACKETT-BURMAN* PLANS AND THE ANALYSIS OF EXPERT OPINIONS, IN ORDER TO ASSESS THE SIGNIFICANCE OF CONTROLLABLE PARAMETERS OF THE PLASMA CUTTING PROCESS

### WYKORZYSTANIE PLANÓW PLACKETTA-BURMANA I ANALIZY OPINII EKSPERTÓW W CELU OCENY ISTOTNOŚCI PARAMETRÓW STEROWALNYCH PROCESU CIĘCIA PLAZMOWEGO\*

This article evaluates the significance of controllable parameters in the plasma cutting process, using the Plackett-Burman Method and the Analysis of Expert Opinions Method. The plasma cutting process was tested using a WPA-6000 Compakt plasma cutter, on non-alloy steel, of the S235JR EN 10025-2:2007 grade, with a carbon equivalent of 0.35%. The effect of the thickness of the sheet, the current flow rate, the cutting speed, the gas pressure during cutting, the height of the torch during cutting, the pierce delay time and the initial pierce height, were analysed. The research revealed the influence of the controllable parameters tested, in the plasma cutting process, on selected output parameters, surface cut drag lines, the width of the kerf at the inlet and outlet, and the value of the perpendicularity of the kerf on the surface of the base. The greatest influences were recorded for intensity of cutting current, cutting speed and gas pressure during cutting. The results obtained were confirmed by the results of the analysis of expert opinions.

*Keywords*: plasma cutting, cutting parameters, the Plackett-Burman method, method for the analysis of expert opinions.

W artykule dokonano oceny istotności parametrów sterowalnych procesu cięcia plazmowego za pomocą metody Placketta-Burmana i analizy opinii ekspertów. Badania procesu cięcia plazmowego przeprowadzono przy użyciu przecinarki plazmowej WPA-6000 Compakt na stali niestopowej konstrukcyjnej gatunku S235JR EN 10025-2:2007 z ekwiwalentem węglowym wynoszącym 0.35 %. Analizowano wpływ grubości blachy, natężenia prądu, prędkości cięcia, ciśnienia gazów podczas cięcia, odstępu palnika od blachy podczas cięcia, czasu dziurkowania oraz wysokości startu. Badania ujawniły wpływ badanych parametrów sterowalnych procesu cięcia plazmowego na wybrane parametry wyjściowe, w szczególności na skok śladów cięcia, na szerokość szczeliny na wejściu i wyjściu oraz na wartość prostopadłości szczeliny do powierzchni bazowej. Największe wpływy zarejestrowano dla natężenia prądu, prędkości cięcia oraz ciśnienia gazu podczas cięcia. Otrzymane wyniki badań zostały potwierdzone wynikami analizy opinii ekspertów.

*Słowa kluczowe*: cięcie plazmowe, parametry cięcia, metoda Placketta-Burmana, metoda analizy opinii ekspertów.

### 1. Introduction

Micro- small- and medium-sized production enterprises, wanting to maintain a competitive advantage, introduce both product and process innovations. Process innovations introduce changes in the processes implemented in the company. One of the key production processes, in steel construction companies, is the cutting process where one of the most popular cutting technologies is plasma cutting [16].

Plasma cutting can be used in the unitary or serial production of steel structures, as well as in various types of overhaul and repair works [10], in both conductive and non-conductive materials [16]. The process of plasma cutting consists in melting and ejecting metal from the cutting kerf with a concentrated, plasma electric arc, glowing between the unprotected electrode and the work-piece being cut. The stream temperature of the plasma is influenced by many factors, including electrical, kinematic and technological factors.

The basic plasma cutting parameters are the intensity of the cutting current, the arc voltage, the cutting speed, the type and the pressure, as well as the rate at which the plasma gas flows, the electrode type and its construction, the diameter of the convergent nozzle and the position of the torch, relative to the work-distance [19].

<sup>(\*)</sup> Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

The incorrect choice of plasma cutting conditions increases the width of the kerf, causes rounding of the upper edges and becomes less than perpendicular. Under other conditions, metal overhangs appear at the bottom edge and there may be no intersection. Along the bottom edge of the cut, dross forms in the form of small, linearly arranged balls of molten material that attach to the surface, creating streaks that are difficult to remove. Also, along the upper edge of the cut, a foamy, somewhat spherical accumulation of molten material collects; however, this can easily be removed. In addition, at the top of the cutting edge, small pieces of molten material collect, randomly [12, 19].

The influence on defects, of the controllable parameters of the plasma cutting process, created during the machining process has been presented in many publications. In [25], the influence of the speed of the feed, on the changes of critical surface features and micro-structure properties, in close proximity to the edges, during plasma cutting, has been shown. The analysis carried out in [3] showed that cutting speed and arc voltage affect the conditions of the formation of the slit and also, that their interaction affects the details when it comes to shaping the slit after cutting. In spite of this, cutting traces may exhibit different profiles, depending on the side under consideration. This effect must be taken into account when designing components for plasma cutting. It has also been emphasised that high-quality parts, viz., Tolerance Class 2, according to ISO 9013, can be obtained as a result of experimental research, aimed at selecting the right values for the parameters of the process.

In [7], the results of testing the width of the slit in the upper and lower zones and the angle of the kerf convergence, are presented and depend on the cutting speed, the thickness of the work-piece and the arc current. A full factor experiment, with three independent variables on two levels, one of the most widespread DoE methods (Design of Experiments) was applied to the present studies. A similar method was used in [4] when investigating the impact of the cutting speed, the flow of the plasma gas and the arc voltage on the quality of the Hardox-400, 12 mm steel cutting surface. In [20], the impact of four parameters was analysed, viz., the impact on the cutting speed, the cutting current, the gas pressure and the height of the torch from the surface of the object and also, their impact on surface roughness, the depth of heat affected zone (HAZ) and the deviation from perpendicularity when cutting S235 steel- with a thickness of 15 mm.

Analysis was carried out using the Taguchi method, which was also used in [5], for analysing the impact, on the air pressure, of the diameter of the nozzle, the velocity, the cutting current and the voltage of the arc and the rate of penetration of the hole in the steel plate. It was shown that when using the 3<sup>4</sup> plans, 81 combinations are required, whereas Taguchi Type L9 plans required a much lower number of combinations.

In [25], a mathematical model was developed in order to optimise the impact of the cutting current, the arc voltage, the cutting speed, the value of the ratio between the cutting height and the start height, the shielding gas pressure and the ratio of allowance to the required width of cutting on the input parameters of the machining process which include the cutting width in the upper and lower parts, the deviations in the kerf sizes at the top and bottom, the angle of inclination of the cutting traces, the roughness of the surface, the rate of dross removal, the percentage ratio (%) between the length of the edges covered with dross and flash/runoff and the total length of the cut. In [14], the laser and plasma, employed in cutting the sheets and boards from medium and high-strength steels, was optimised. As independent parameters, the intensity of the current, the cutting speed, the distance between the nozzle and the object and gas pressure were used. Deviations from perpendicularity, with regard to the kerf, the roughness of the surface after cutting, as also the dimensions of the dross were optimised. In [13], it was found that when cutting thick, steel plates, the correct choice made, regarding the intensity of the

cutting current, as well as the cutting speed, affects the width and the straightness of the cut as also the roughness of the cut surface and the depth of the thermal influence zone. The cutting quality of S355 structural steel was examined in [24]. It was found that when controlling the cutting speed, the topography of the cutting surface and the micro-structure of the thermal influence zone depend on the type of gases used. Investigations of the thermal impact zone for the austenitic plasma cutting of steel with a thickness of 10 - 30 mm and cutting speeds of 710 - 2030 mm/min, were carried out in [15]. It was found that these factors significantly affect structural changes and the micro-hardness of the zone analysed.

Thus, many factors are important in the plasma cutting process; this makes it difficult to regulate and ensure that the requirements of ISO 9013 are complied with. The few attempts to use DoE methods for this purpose either significantly limit the number of factors studied or require a large amount of research. The use of the Taguchi method requires the implementation of tests at several variable levels, which is not always easy. As a solution to the problem, DoE uses and applies methods such as the Plackett-Burman plans. These are the saturated plans, so-called, which require a number of tests, viz., N=k+1, where k - the number of variables tested- which should be a multiplicity of 4.

At present, saturated plans for 4, 7, 11, 15, 19, 23, 27, 31, 35, 39, 43, 47, 63 and 127 variables have been developed [9]. Such plans are widely used in various research areas, in such as the production of nanoparticles [21], drugs [8, 11], polymers [1], and fuel production [2]. The development of the Plackett-Burman method is presented in [18, 22]. The limitation of the above-mentioned plans is the requirement to ensure that tests are carried out at strictly defined points, which limits the scope of changes in the factors analysed. On the other hand, this method affords the opportunity to perform accurate statistical calculations, in particular, to calculate multidimensional linear regression coefficients [9, 23].

The purpose of the present study is to assess the significance of controllable parameters in plasma cutting, using Plackett-Burman plans and expert assessment methods.

### 2. Test conditions

One of the most widely used types of steel in steel construction was used for the present research, namely, unalloyed structural steel of the S235JR EN 10025-2: 2007 grade- formerly St3S steel- with a carbon equivalent of 0.35%.

Tests on plasma cutting were carried out using the WPA-6000 Compakt plasma cutter with a SMART CNC control programme equipped with a table with CNC control and the 133WDM ForCut plasma source. The cutter was equipped with two burners, *viz.*, a plasma burner for cutting boards, with a thickness of up to 30 mm and a gas burner for cutting boards, with a thickness of up to 150 mm. Compressed air was applied as a plasma-forming and protective gas and was supplied to the cutting zone through air filters and a dryer. An illustration of the plasma cutting and the basic schematic of plasma torch, are shown in Fig. 1.

An analysis was performed of the influence of the controllable parameters of the plasma cutting process, on the output parameters of 7, technological factors, namely sheet thickness, cutting current, cutting speed, gas pressure during cutting, height of the torch during cutting, pierce delay time and initial pierce height. The elimination analysis plan, based on the Plackett-Burman method, is presented in Table 1.

The range of changes in the factors studied, was selected experimentally, so that all associations of values could be realised. In Fig. 2 the cutting parameters examined along with characteristic views of the samples are presented. The following cutting parameters were examined, namely, the cutting stroke traces (P), the width of the kerf at the entrance (sg) and at the exit (sd), the height of the discharges/dross





Fig. 1. Plasma cutting (a) and schematic of plasma torch (b)



Fig. 2. Sample after plasma-cutting: a) schematic diagram of the test factors, b) lateral surface of the slit, c) lower surface of the sample

Table 1. Plan and test conditions

	Values and codes for the test factors													
Test point no.	Metal sheet thick- ness [mm]	X1	Cutting current [A]	X2	Cutting speed [mm/ min]	X3	Gas pressure during cutting [bar]	X4	Height of the torch during cutting [mm]	X5	Pierce delay time [s]	X6	Initial pierce height [mm]	X7
1	4	-1	80	-1	2600	-1	6	1	3.5	1	0.4	1	4	-1
2	12	1	80	-1	2600	-1	5	-1	3	-1	0.4	1	7	1
3	4	-1	130	1	2600	-1	5	-1	3.5	1	0.1	-1	7	1
4	12	1	130	1	2600	-1	6	1	3	-1	0.1	-1	4	-1
5	4	-1	80	-1	6500	1	6	1	3	-1	0.1	-1	7	1
6	12	1	80	-1	6500	1	5	-1	3.5	1	0.1	-1	4	-1
7	4	-1	130	1	6500	1	5	-1	3	-1	0.4	1	4	-1
8	12	1	130	1	6500	1	6	1	3.5	1	0.4	1	7	1

(h), the deviation of the perpendicularity of the sides of the kerf in relation to the base surface ( $\Delta$ ) and the values of the arcs of the fracture surface on both the left (RL) and right (RP) sides.

The calculations were made using Statistica 13.3 Software, where the coefficients of linear regression equations were calculated on the basis of Pareto coefficients and the significance of the influence of the test factors, on the selected output parameters of the cutting process, was determined.

Analyses of the results of questionnaire surveys, conducted among experts, were made using the comparison in pairs method, such as the

Kendall Tau Correlations method and the Spearman Rank Order Correlations method; Statistica 13.3 Software was also used. A probability level of 95% was assumed.

### 3. Results of the study

An example of the results of the calculation of the coefficients of regression equations and Pareto coefficients is presented in Fig. 3. Values of coefficients  $b_0$ ,  $b_1$ ,  $b_i$  are suitable for the equation:

$$y = b_0 + \sum_{i=1}^n b_i X_i , \qquad (1)$$

and prove the following:  $b_0$  - regarding the level of influence of the size tested,  $b_i$  - regarding the intensity and direction of factors  $X_1$  ...  $X_i$  - on the test size.



Fig. 3. The influence of test parameters on the stroke of the cutting traces, q.v. the results of calculations and the Pareto diagram.

studied

	9
	,
	9
3         7         3         4         1         2         5         6         8           4         6         4         5         2         1         3         7         9           5         6         3         2         1         5         4         7         8           6         7         5         3         9         2         1         4         6           7         6         5         4         7         2         1         3         9	7
4         6         4         5         2         1         3         7         9           5         6         3         2         1         5         4         7         8           6         7         5         3         9         2         1         4         6           7         6         5         4         7         2         1         3         9	9
5         6         3         2         1         5         4         7         8           6         7         5         3         9         2         1         4         6           7         6         5         4         7         2         1         3         9	8
6         7         5         3         9         2         1         4         6           7         6         5         4         7         2         1         3         9	9
7 6 5 4 7 2 1 3 9	8
	8
8 3 7 1 6 2 4 5 8	9
9 10 9 8 3 1 2 6 5	7
10 7 4 3 9 1 2 6 5	8
11         8         3         7         6         1         2         4         5	9
12         6         2         4         5         1         3         8         9	7
13 7 4 5 6 2 1 3 8	9
14         6         5         7         2         3         1         4         8	9
15 6 4 5 3 1 2 8 9	7

Table 3. Results of studies on the assessment of the conformity of expert opinions

According to the (DoE) planning principles of the research, values  $X_{1...}X_i$  were used as relative, in the range from -1 (minimum) to +1 (maximum).

When analysing the results of statistical calculations, it was determined that all the parameters examined affect the stroke of the-surface cut drag lines. The width of the kerf at the inlet and outlet does not affect the initial pierce height nor does it affect the deviation of the sides of the kerf to the base surface, namely, the start height and gas pressure. The height of the flash dross depends solely on the gas pressure, the thickness of the sheet and the cutting current. However, the radius of the arcs of the kerf is completely uncontrollable. The conclusions presented confirm the calculated coefficients of  $R^2$  determination of the regression dependencies, presented in Table 2.

Regression dependencies, important for calculating the size of the values examined, with a probability of 0.95, are presented below. Dependence data can be used in the same way as is used for the calculation of the expected values of the factors tested, as well as for the development of the optimisation programme, by such as the linear programming method.

Table 2. Coefficients of  $R^2$  determination of the calculations of the factors

Coefficients of R <sup>2</sup> determination for									
The stroke of cutting drag lines	The width of the kerf at the entrance	The width of the kerf at the exit	Dross buildup	Deviation of perpen- dicularity	Kerf arc on the left side	Kerf arc on the right side			
0.9607	0.9831	0.9820	0.7050	0.9606	0.1183	0.1239			

The regression dependencies, obtained for the range of cutting parameters studied, are presented below:

<ul> <li>the stroke of cutting drag lines:</li> <li>P = 1.239+0.175X1-+0.405X20.128X3-+0.358X40.258X5 +0.572X60.262X7-;</li> </ul>	(2)
• width of the kerf at the entrance: sg = 2.168+0.122X1-+0.412X20.205X30.06X4-+0.04X5 +0.067X6;	(3)

• width of the kerf at the exit:

sd = -1.7290.442X1 + 0.472X20.628X30 - .285X5 - +0.095X6+0.172X7;(4)

- dross buildup: h = 0.856 + 0.209X10.187X20.384X4 -; (5)
- deviation in the perpendicularity of the sides to the base surface:  $\Delta = 0.800 - + 0.220 \times 10.243 \times 2 + 0.258 \times 3 + 0.110 \times 50.207 \times 6^{-};$ (6)
- the value of the arches of the kerf surface on the left side RL = 3.987 mm;
- the value of the arcs of the kerf surface on the right-side RP = 5.532 mm,

where  $X1 \dots X7$  – normalised values for sheet thickness, intensity of cutting current, cutting speed, gas pressure during cutting, height of the torch during cutting, pierce delay time and pierce height, respectively.

Analyses of this kind makes it possible to minimise production losses, as they allow technological factors to be decided which could be the basis for effective process control and a guarantee of the required effects.

The results of the **Plackett-Burman** method were compared with the results of the analyses of expert opinions. In order to determine the validity of plasma cutting parameters, a survey was conducted among micro and small enterprises producing steel constructions with the help of expert opinions. Employees from 15 Polish companies, with a minimum of 5-years' experience in the field of cutting sheet metal played the role of the experts. In the study, the experts assessed the significance of the parameters affecting plasma cutting. The following parameters were specified, viz., preflow gas pressure, cutflow gas pressure, height of the torch during cutting, arc voltage, cutting current, cutting speed, initial pierce height, pierce delay time and height of the torch during piercing numbered from 1 to 9 by rank (1 being the highest rank in the parameter). The results of the research are presented below (Table 3). Data analysis included verification of the compliance of expert opinions regarding the importance of individual parameters affecting plasma cutting. For this purpose, the Kendall-Smith Concordance coefficient [6] was applied. For the assessments of the 9 parameters made by 15 experts, the value of the Kendall-Smith Index obtained, was at the level of 0.608. The significance of the concordance coefficient was assessed using the chi-square o (k1–) degrees of freedom, where k: number of parameters being evaluated. From the chi-square distribution tables [8] it follows that for df = 8 – and a significance level of 0.95 – there are grounds for rejecting the null/zero hypothesis, which means that the convergence of expert opinions is not accidental and there is consensus in their positions.

For the study group in question, an analysis was also carried out using the Comparison in Pairs method, such as the Kendall Tau Correlations method (Table 4):

The results of the analysis show a significantly positive relationship between parameters 1 and 3, 6 and 7, with the most significantly positive relationship being between parameters 5 and 9. Negative relations between parameters 2 and 6, 4 and 6 and 1 and 8 were also recorded. These relationships are marked in red in Table 3. The occurrence of these relationships was confirmed by the Spearman Rank-Order Correlations method. The following results were obtained for pairs of parameters that were characterised by a positive relation: for 1 and 3: R = 0.519, t (N2–) = 2.192, p = 0.047, for 6 and 7: R = 0.648, t (N2–) = 3.066, p = 0.009, for 5 and 9: R = 0.590, t (N2–) = 2.632, p = 0.021. For parameter pairs 1 and 8, the following values were obtained R = -0.790, t (N2–) = -4.639, p = 0.000, for parameters: 4 and 6: R = -0.517, t (N2–) = -2.180, p = 0.048, where R: Spearman's Correlation coefficient, t - significance test. The negative relationship between parameters 2 and 6 was not confirmed.

As a consequence, the validity ranking for the parameters tested in the plasma cutting process was determined on the basis of sorting the average values of expert assessments. In Fig. 4, the parameters examined were segregated, according to the principle where the highest validity corresponds to the lowest average value.

Based on the above analysis, it was found that the most important parameters in the plasma cutting process are intensity of cutting current, cutting speed and cutflow gas pressure, thus confirming the effectiveness of using DoE methods, including the Plackett-Burman plans, in order to assess the significance of controllable process parameters in the plasma cutting process.

### 4. Conclusions

As a result of the research, the influence of basic plasma cutting factors on the characteristics of the cutting of carbon steel sheets, with a thickness of 4 - 12 mm, was determined. In order to determine the importance of the influence of the factors studied, the Plackett-Burman saturated plans, so-called, were used, ensuring, on the one hand,

Parameters tested	1	2	3	4	5	6	7	8	9
1	1	- 0.203	0.418	0.113	-0.37	-0.134	-0.186	-0.691	-0.119
2	-0.202	1	-0.065	0.139	0.246	-0.379	-0.219	-0.034	-0.012
3	0.417	-0.065	1	-0.229	-0.340	-0.178	-0.074	-0.113	-0.267
4	0.113	0.139	-0.229	1	-0.172	-0.405	-0.335	-0.266	-0.059
5	-0.371	0.246	-0.340	-0.172	1	-0.092	-0.316	0.201	0.547
6	-0.134	-0.379	-0.178	-0.405	-0.092	1	0.517	0.083	0.025
7	-0.186	-0.219	-0.074	-0.335	-0.316	0.517	1	0.204	-0.354
8	-0.691	-0.034	-0.113	-0.266	0.201	0.083	0.204	1	-0.103
9	-0.119	-0.012	-0.269	-0.059	0.547	0.025	-0.354	-0.103	1

Table 4. Results of studies on the assessment of the conformity of expert opinions



minimisation of the number of tests as compared to other methods while on the other hand, giving a detailed statistical analysis of the measurement results. The equations of multidimensional linear regression obtained were confirmed by the opinion of expert practitioners. The relationships between the parameters were determined and the three most important parameters in the plasma cutting process were indicated *viz.*, intensity of current, cutting speed and gas pressure during cutting.

The application of the existing dependencies, in a production company, opens up the possibility of minimising production losses while the plasma cutting process is still being developed; this is based on a significant assessment of the process of the controllable parameters of plasma cutting.

Fig. 4. The significance of parameters in the plasma cutting process according to the expert opinion method

### References

- 1. Abd El Aty A A, Wehaidy H R, Mostafa F A. Optimization of inulinase production from low cost substrates using Plackett–Burman and Taguchi methods. Carbohydrate Polymers 2014; 102: 261-268, https://doi.org/10.1016/j.carbpol.2013.11.007.
- 2. Azizi D, Gharabaghi M, Saeedi N. Optimization of the coal flotation procedure using the Plackett–Burman design methodology and kinetic analysis. Fuel Processing Technology 2014; 128: 111-118, https://doi.org/10.1016/j.fuproc.2014.06.021.
- 3. Bini R, Colosimo B M, Kutlu A E, Monno M. Experimental study of the features of the kerf generated by a 200 A high tolerance plasma arc cutting system. Journal of Materials Processing Technology 2008; 196(1-3): 345-355, https://doi.org/10.1016/j.jmatprotec.2007.05.061.
- 4. Chamarthi S, Reddy N S, Elipey M K, Reddy D V R. Investigation Analysis of Plasma arc cutting Parameters on theUnevenness surface of Hardox-400 material. Procedia Engineering 2013; 64: 854-861, https://doi.org/10.1016/j.proeng.2013.09.161.
- 5. Chen J C, Li Y, Cox R A. Taguchi-based Six Sigma approach to optimize plasma cutting process: an industrial case study. International Journal of Advance Manufacturing Technology 2009; 41: 760-769, https://doi.org/10.1007/s00170-008-1526-1.
- 6. Cieslak M. (red.) Prognozowanie gospodarcze. Metody i zastosowania. Warszawa: PWN, 2001.
- Dodun O, Bangu S I, Slătineanu L, Coteață M. Kerf Generation during the Plasma Cutting Process. AIP Conference Proceedings 2016; 1769(1): 1-6, https://doi.org/10.1063/1.4963436.
- Elazazy M S, El-Hamshary M, Sakr M, Al-Easa H S. Plackett-Burman and Box-Behnken designs as chemometric tools for microdetermination of L-Ornithine, Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 2018; 193: 397-406, https://doi. org/10.1016/j.saa.2017.12.044.
- 9. Elektroniczny Podręcznik Statystyki PL. Krakow: StatSoft, 2006. WEB: http://www.statsoft.pl/textbook/stathome.html
- 10. Gawlik J, Plichta J, Świć A. Procesy produkcyjne. Zarządzanie i inżynieria produkcji. Warszawa: PWE, 2013.
- Hassan M, Essama T, Yassina A S, Salam A. Optimization of rhamnolipid production by biodegrading bacterialisolates using Plackett– Burman design. International Journal of Biological Macromolecules 2016; 82: 573-579, https://doi.org/10.1016/j.ijbiomac.2015.09.057.
- 12. Jak poprawić jakość cięcia plazmą /www.hyperthermcom
- Kim S-I, Kim M-H. Evaluation of Cutting Characterization in Plasma Cutting of Thick Steel Ship Plates. International Journal of Precision Engineering and Manufacturing 2013; 14: 1571-1575, https://doi.org/10.1007/s12541-013-0212-x.
- Klimpel A, Cholewa W, Bannister A, Luksa K, Przystałka P, Rogala T, Skupnik D, Cicero S, Martín-Meizoso A. Experimental investigations of the influence of laser beam and plasma arc cutting parameters on edge quality of high-strength low-alloy (HSLA) strips and plates, International Journal of Advance Manufacturing Technology 2017; 92: 699–713, https://doi.org/10.1007/s00170-017-0119-2.
- Lazarevic A, Lazarevic D. Investigations of material hardness and structural changes in the heat-affected zone during plasma cutting. Weld World 2017; 61: 1069-1075, https://doi.org/10.1007/s40194-017-0510-5.
- 16. Pilarczyk J. Poradnik inżyniera. Spawalnictwo. T. 2. Warszawa: WNT, 2005.
- 17. Quinlan K R, Lin D K J. Run order considerations for Plackett and Burman designs. Journal of Statistical Planning and Inference 2015; 165: 56-62, https://doi.org/10.1016/j.jspi.2015.04.001.
- 18. Raport: cięcie plazmą przewodnik po technologii. Projektowanie i Konstrukcje Inżynierskie 2007; 2: 16 21.
- 19. Salonitis K, Vatousianos S. Experimental Investigation of the Plasma Arc Cutting Process. Procedia CIRP 2012; 3: 287-292, https://doi. org/10.1016/j.procir.2012.07.050.
- 20. Shah S R, Parikh R H, Chavda J R, Sheth N R. Application of Plackett–Burman screening design for preparing glibenclamide nanoparticles for dissolution enhancement. Powder Technology 2013; 235: 405-411, https://doi.org/10.1016/j.powtec.2012.10.055.
- 21. Shen L, Morris M D. Augmented Plackett–Burman designs with replication and improved bias properties. Journal of Statistical Planning and Inference 2016; 179: 15-21, https://doi.org/10.1016/j.jspi.2016.07.003.
- 22. Taavitsainen V-M T. Experimental Optimization and Response Surfaces. In: Varmuza K (ed.) Chemometrics in Practical Applications. Rijeka: InTech, 2012 91-138.
- 23. Thomas D J. Optimizing Plasma Cut-edge Properties for Improving the Durability of Bridge Structures. International Journal of Steel Structures 2011; 11(4): 481-493, https://doi.org/10.1007/s13296-011-4007-6.

- 24. Thomas D J. The influence of the laser and plasma traverse cutting speed process parameter on the cut-edge characteristics and durability of Yellow Goods vehicle applications. Journal of Manufacturing Processes 2011; 13(2): 120-132, https://doi.org/10.1016/j. jmapro.2011.02.002.
- 25. Yang S Y S. An Expert System for Plasma Cutting Process Quality Prediction and Optimal Parameter Suggestion, in: Mo J P T et al. (eds.) Global Engineering, Manufacturing and Enterprise Networks. New York: Springer Science+Business Media 2001: 438-445, https://doi. org/10.1007/978-0-387-35412-5\_51.

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### A METHOD OF COMPARATIVE STUDIES ON CHECKUP SETS TO EVALUATE THE TECHNICAL CONDITION OF TRACTORS

### METODA BADAŃ PORÓWNAWCZYCH ZBIORÓW SPRAWDZEŃ DO OCENY STANU TECHNICZNEGO CIĄGNIKÓW\*

In this paper the authors propose an original method of the numerical evaluation of checkup sets for the technical condition of an agricultural tractor. Information entropy required in diagnostic tests for a specific checkup set was used as the evaluation criterion. A formal description is given for the technical condition diagnostics of a tractor in its operation period, which is characterised by a high rate of average damage. The structural model was constructed using information entropy. This model accumulates the number of checkups, probability of specific damage types and assigns them a common numerical measure. The conducted logic analysis of the proposed method and the results obtained in experiments on its practical applicability in service stations indicate that the method adequately describes this area of machine operation and thus may be a measure of information effectiveness for checkup sets determining the machine technical condition.

Keywords: agricultural tractor, technical condition, checkup set, information entropy.

W pracy zaproponowano oryginalną metodę liczbowej oceny zbiorów sprawdzeń stanu technicznego ciągnika rolniczego. Jako kryterium oceny wykorzystano entropię informacyjną, konieczną do uzyskania w badaniach diagnostycznych dla odpowiedniego zbioru sprawdzeń. Wykonano formalny opis procesu oceny stanu technicznego ciągnika w systemie eksploatacji, który charakteryzuje duży udział uszkodzeń awaryjnych. Do budowy modelu strukturalnego wykorzystano entropię informacyjną, Model ten kumuluje w sobie liczbę sprawdzeń, prawdopodobieństwo wystąpienia określonych uszkodzeń i nadaje im wspólną miarę liczbową. Przeprowadzona logiczna analiza proponowanej metody oraz wyniki uzyskane w badaniach z jej praktycznego zastosowania w zakładach serwisowych wskazują, że opisuje adekwatnie ten obszar eksploatacji maszyn i może być miarą efektywności informacyjnej zbiorów sprawdzeń stanu technicznego maszyn.

Słowa kluczowe: ciągnik rolniczy, stan techniczny, zbiór sprawdzeń, entropia informacyjna.

### 1. Introduction

In order to ensure efficient machine operation processes various decisions need to be made on an on-going basis and their accuracy is a function of the amount and quality of available information on the process itself and on its environment. Generally the efficiency of performance in the case of technical objects is defined as the degree, to which they meet reliability, economic, quality requirements, etc., within a specific period of time in relation to incurred outlays or inputs [7]. Based on these requirements specific operation strategies are implemented, covering machine use and servicing processes as well as their interdependencies evaluated according to specific criteria [10].

Physical aging of machines, understood as a deterioration of their technical condition, is an objectively existing reality during their use. Current information on the technical condition of machine is crucial in production maintenance. We obtain such information e.g. based on measurements of specific parameters in operation processes as well as assisting processes.

Machine operation and the related processes are investigated in the analyses performed in the economic system, with economic efficiency used as the primary evaluation criterion. This also pertains to the collection and analysis of information on the technical condition of machines. Thanks to advances in measurement methods provided e.g. by the application of electronics and IT tools, the collection of information is an increasingly simple process [1, 17]. In turn, a greater role is played by planning and efficiency of taken measurements as well as analytical methods applied for the resulting information. A combination of these two areas makes it possible to obtain valuable information, which effectively supports management of machine operation processes [7].

Structural formal models are constructed for diagnostic processes in order to conduct simulation studies and evaluate their efficiency based on various criteria. These problems include the theory of construction of diagnostic tests [13], using e.g. the matrix method, the deletion method, etc. [19].

In this respect an essential role is attributed to checkup sets (measurement sets), which are used to determine the machine technical condition, as well as their number and types, sequence, labour intensity and generated costs.

This paper presents a method to evaluate checkup sets in order to diagnose the technical condition of a tractor, after the occurrence of a specific signal (symptom) using information entropy. Examples of checkup sets are given, which results will be used to evaluate their information effectiveness and indicate areas of practical applications for the developed method.

<sup>(\*)</sup> Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

### 2. Characteristics of tractor operation processes in agriculture

Analyses of machine operation processes need to include their relationships with the environment [2]. Tractors as energy converting machines have found numerous applications in many sectors of the economy (agriculture, transport, construction industry, etc.). They are highly complex and costly technical objects, being sources of mechanical energy for many other machines. Maintenance of cooperating machines depends on their design characteristics and the role they serve in the production process. Their operation strategy needs to be adapted to specific conditions, applying adequate criteria for its evaluation [4, 10, 12]. Agricultural tractors cooperate with many machines, perform a variety of jobs depending on the season, most frequently in difficult terrain and under harsh weather conditions. Together with the cooperating machines they form series reliability systems, with failure causing downtime of the entire line. Such an environment of the system of their operation generates numerous cases of average damage, which are random in character and this fact needs to be considered in the strategy of their maintenance assurance. As in the case of most machines a major role in the maintenance of tractors is played by preventive maintenance in the form of preventive maintenance inspections. The inspections are performed following generally applied guidelines. In view of the high share of average damage in the operation of agricultural tractors reactive maintenance needs to be executed simultaneously. This strategy reduces efficiency of machine operation, at the same time generating additional costs and losses. They result from multiple problems in this area [6].

In the case of failure it is necessary to identify its cause promptly and to restore the tractor to operating condition after its random loss, which is a pre-requisite for its further operation and minimisation of economic losses.

In decision making processes it is essential to have information on the current technical condition of the tractor, its assemblies and parts. Machine operation practice has provided numerous methods to identify, record and measure signals on the technical condition of machines, based on which diagnostic information is obtained [2, 17].

This task is performed by service mechanics, most frequently on site, since they can use a mobile workshop truck offering limited, but increasingly advanced servicing equipment. Firstly an adequate checkup set needs to be performed, typically measurements to obtain precise information on the damaged/faulty element. In such a case a binary evaluation of the technical condition for the machine and its parts is sufficient, equation (1):

$$I(c_i) = \begin{cases} 1, gdy \ c_i \in \{C_1\} \\ 0, gdy \ c_i \in \{C_2\} \end{cases}$$
(1)

where:

 $I(c_i)$  – information on the technical condition of the i-th part,

- $\{C_1\}$  a set of parts in working order,
- $\{C_2\}$  a set of faulty/damaged parts.

Thus we obtain information whether an object (tractor, assembly, part) is in working order (function value 1) or damaged/faulty (function value 0).

The structure of the process evaluating the technical condition (diagnostics) as a subsystem of machine operation is presented in Fig. 1.

The technical condition of a tractor may deteriorate due to specific wear of its part(s) or assembly, which in terms of machine reliability is referred to as damage/fault. A machine which is inoperative emits a specific signal (symptom), which is a set of information and accompanies specific types of wear. A diagnostic signal in a tractor may be manifested as a loss of engine power, increased fuel consumption, ele-



Fig. 1. A flow chart for the process evaluating the technical condition of tractors

vated temperature, vibrations, excessive smoke from the exhaust, loss of specific work features, etc. For example, a reduced engine power (signal) may indicate an excessive piston to cylinder wall clearance, valve wear, a blown head gasket, etc.

After the signal has been identified, specific checkups or their sets need to be performed in order to obtain information on damage. Thus provided information will be used in order to undertake an adequate service decision as well as a machine operation decision. The minimal checkup set is considered to be of greatest merit, as it makes it possible to determine the technical condition of a machine at the lowest number of checkups, lowest costs and labour consumption, etc. It is the primary requirement for efficient diagnostics [14]. In exceptional cases the signal will be diagnostic information, if it is emitted by only one worn part. Relationships between the diagnostic signal and information on the type of wear are complex. The following assumptions were adopted within this study:

- Every part or assembly of a tractor may be operational or faulty/ damaged and binary logics will be used in their theoretical description,
- A deterioration of the technical condition or the fault of a tractor or its assemblies is caused by damage to only one of its parts, which is partly confirmed by servicing practice,
- We diagnose random average damage.

A method needs to be developed to rationalise the number and types of checkups required for the evaluation of the technical condition of tractors.

### 3. Aim of the study

A problem faced within this study is connected with a lack of an objective, numerical valuation of checkup sets (diagnostic tests) based on the criterion of the amount of information required for the determination of the technical condition of tractors using these sets or tests.

This problem may be solved thanks to the construction of an adequate abstract system, the establishment of a database as well as logic verification and practical evaluation of applicability of the developed method. This should result in the development of a universal and objective method, facilitating a comprehensive, numerical evaluation of checkup sets so that diagnostic information may be provided by the signal. The criterion in this evaluation will be based on the amount of required minimal information necessary for the determination of the technical condition of an object after a specific signal is received. This information will be a function of the number and types of required checkups, their complexity and costs, their sequence, etc.

Checkup sets will be used to identify random damage, thus in the developed method probabilistic models were used and the obtained results may be referred to an adequately numerous population of tractors.

In order to achieve the planned objective the following tasks need to be performed:

- identification of the specific character of operation of tractors in agriculture,
- analyses of the evaluation process for the technical condition of tractors in service centres,
- development of an objective valuation and comparison method for checkup sets used in the evaluation of the technical condition of tractors,

• a logic and empirical evaluation of the developed method,

 indication of potential areas for its practical application based on examples.

### 4. Material and Research Methods

This study is methodological in character and will provide a universal valuation and comparison method for checkup sets determining the technical condition of tractors in their servicing processes. Requirements imposed on the developed method, such as universality, objectivity, comprehensiveness and establishment of a numerical informative evaluation of checkup sets may be met thanks to the construction of a structural model for a deduction process evaluating the technical condition of tractors together with an empirical database.

An inspiration for the development of this method has been provided by the development of basic science, particularly mathematics, which may find further practical applications. An effective combination and utilisation of advances in mathematics and the practical execution of machine operation processes will facilitate development of the new method. Its application will provide in-depth knowledge on machine operation processes and ensure their rationalisation, which is also of practical importance.

The first stage consisted in a description of the formal process of tractor technical condition assessment. The flow chart of the process (Fig. 1) may be described by equation (2):

$$S = \left\{ N_i \left( p_i \right) \right\} \tag{2}$$

where:

- S a signal for the technical condition,
- $N_i$  a set of potential variants of information contained in the signal,
- $p_i$  probability of occurrence of i-th information.

Specific relationships are found between the signal, damage, checkups and information (Fig. 2).



Fig. 2. A diagram for the relationship between the signal – damage/fault – checkup – information.

Each signal *S* contains a certain set of information variants on damage/fault in part  $c_i$  and the probability of occurrence of this damage  $p_i$  (Fig. 2). An adequate checkup is required to obtain information from the signal. It was assumed in this study that checkup  $\pi_i$  has to be performed to obtain each item of information 2. The complete evaluation of the technical condition of a tractor requires the execution of checkup set  $\{\Pi_i\}$ .

Such a process may be described analytically based on the information theory proposed by Shannon [18], with information entropy as the basic concept. This facilitates quantitative valuation of information, which needs to be acquired when investigating a random process; this approach has been successfully used in many areas.

Information entropy has been applied in the formal description of studies on sliding journal bearings at a test stand [20]. As a result a novel and practically useful method was developed for the diagnosis of manufacturing errors in rolling bearings of aircraft engines. In study [15] a method using information entropy was developed to monitor vibrations in the milling process. The value of information entropy was a measure of instability in the work of a machine tool. Information entropy has been applied to valuate the technical condition of machines comprising the system when designing manufacturing systems [9]. Information entropy is a method of modelling random processes in many areas of science and thanks to its clear and logic structure it may be successfully used in practice [8, 11, 16].

Available literature lacks examples of applications for information entropy in processes of technical condition evaluation for agricultural tractors. Due to the random character of the occurrence of damage/ fault information entropy may prove to be useful in modelling of the evaluation process for the machine technical condition using checkup sets identifying damage.

An empirical system composed of a set of damage/fault variants and the probability of their occurrence, constituting missing information in the evaluation of the technical condition of tractors, may be described using the statistical information theory with equation (3) of information entropy [18]:

$$H = -\sum_{i=1}^{n} p_i \log_2 p_i , \qquad (3)$$

where:

- $n_i$  the number of variants of information on damage/fault,
- H the amount of needed information (bit),
- $p_i$  probability of occurrence of the i-th variant of damage/ fault in the signal.

If in equation (3) we apply a logarithm with the base of 2, then the amount of information entropy is obtained in bits. It results from equation (3) that the value of information entropy H is a function of the number of possible damage/fault variants  $n_i$  contained in the signal and probability of their occurrence  $p_i$ . In the case of clustered probability distribution, in which it is easy to predict which part is faulty/damaged, the value of entropy decreases. Then the checkup set required to obtain information on the technical condition of a tractor will be optimal. Particularly when the signal contains only one variant of fault/damage, with the probability of distribution of 1, the value of entropy will be 0. This is equivalent to complete information on the machine technical condition and thus results in no need for checkups. If the diagnostic signal contains a numerous set of fault/damage variants with a small and uniform probability of their occurrence  $(p_i = 1/n)$ , information entropy takes the maximum value. It may be calculated from equation (4) of the structural information theory:

$$I = log_2 n_i \tag{4}$$

where:

- *I* the amount of information according to the structural information theory (bit),
- $n_i$  the number of information variants on fault/damage.

Then a numerous checkup set needs to be executed to obtain information on the machine technical condition.

In the practical execution of processes evaluating the machine technical condition the probability of occurrence of a specific type of wear and information on that wear may be differentiated based on studies on machine operation, experience of service mechanics and information obtained from machine operators.

From the point of view of diagnostics the case described by equation (3) is more advantageous in comparison to that described by equation (4), since the amount of information, which needs to be obtained in tests - and as a result also the incurred outlays - will be smaller.

Knowing the diagnostic signal and potential information it contains we may construct adequate checkup sets to evaluate the machine technical condition. These sets will differ in the number and type of checkups as well as the sequence of their execution. From equations (3) and (4) we may calculate the numerical value of the information, which needs to be obtained and the required adequate checkup set, which makes it possible to acquire complete information on the technical condition of a tractor. Such a checkup set will be characterised by the smallest information entropy. As a result equations (3) and (4) provide a numerical valuation and comparison of checkup sets based on the criterion of their information entropy and in this respect constitute an abstract model, which logic accuracy and practical applicability need to be verified. It constitutes a subsystem of the general model of the machine operation process [3, 5].

It results from the logic analysis of equations (3) and (4), as well as the actual evaluation of the tractor technical condition that information entropy of a checkup set verifying the technical condition:

- reaches the value of zero when the signal contains information on only one specific damage, i.e. the signal is then diagnostic information,
- reaches the maximum value when each checkup from a checkup set identifies a specific fault/damage type with equal probability,
- decreases when each checkup from a checkup set identifies specific information variants with different (clustered) probability,
- increases with an increase in the size of the checkup set required for a complete identification of the machine technical condition.

The presented dynamics of changes in information entropy is fully adequate for the informative description of checkup sets in the evaluation of the tractor technical condition. In terms of logics equations (3) and (4) may be used to calculate the amount of information (information entropy) generated by respective checkup sets to evaluate the tractor technical condition.

The practical utilisation of the developed method needs to be verified. For this purpose empirical studies have been performed concerning tractor servicing.

### 5. An example application for the method

Analyses were conducted on agricultural tractors, in which a specific fault occurred. A signal on the fault was displayed on the onboard computer as the fault code or after an external computer with software compatible with the tested tractor was connected. The fault code or message is a signal, which generates a series of potential damage types. Typically one signal denotes several variants of damage. In such a situation the person verifying the technical condition has to make a decision what checkups to perform and in what sequence.

Tests were performed on 72 agricultural tractors of the same type, in which the signal of fault indicated an excessively high temperature of the engine. For such a signal specific checkup sets were established, which will provide complete information on the technical condition of the tractor engine.

item	Type of checkup	Probability of fault/damage occurrence for tested checkup sets					
		1	2	3			
1.	Faulty thermostat	0.067	0.053	0.181			
2.	Too low coolant level	0.067	0.053	0.151			
3.	Too low engine oil level	0.067	0.053	0.102			
4.	Oil cooler damage	0.067	0.053	0.079			
5.	Loose or broken coolant pump V-belt	0	0.053	0.079			
6	Faulty temperature sensor	0.067	0.053	0.134			
7.	Fan damage	0.067	0.053	0.031			
8.	Faulty fan clutch assembly	0.067	0.053	0.031			
9.	Fouled radiator core	0.067	0.053	0.031			
10.	Faulty temperature transmitter	0.067	0.053	0.055			
11.	Clogged coolant system pipes	0.067	0.053	0			
12.	Blown head gasket	0.067	0.053	0			
13.	Cracked head	0.067	0.053	0			
14.	Cracked engine block	0.067	0.053	0			
15.	Coolant pump damage	0.067	0.053	0			
16	Broken coolant system pipe	0	0.053	0.031			
17.	Engine overload	0.067	0.053	0.063			
18.	Radiator drain plug damage	0	0.053	0.031			
Values	of information entropy for checkup sets (bits)	3.92	4.04	3.42			

Table 1. Checkup sets for the signal indicating "excessively high temperature of the tractor engine"

The first checkup set was developed based on the technical specifications of the manufacturer and data given in the diagnostic computer system for this signal (Table 1). Analysis of data facilitated the construction of a checkup set, but did not make it possible to differentiate the probability of occurrence of individual variants of fault/ damage.

The second checkup set was developed using additionally the results of a questionnaire survey conducted among 127 service mechanics, who were performing analyses of the technical condition of these tractors. Based on their experience and machine operation conditions the respondents supplemented the first checkup set with additional checkups (Table 1). They included fault/damage types, which occurrence had not been predicted by the tractor manufacturer.

The third checkup set was created with the use of the survey, in which the respondents indicated damage most commonly diagnosed in their practice. The probability of each damage type, identified by a respective checkup, was calculated on this basis. For each of the three checkup sets, the amount of required information (information entropy) was established using equations (3) and (4). Results of these calculations are presented in Table 1.

It results from data collected in Table 1 that using equation (3) we may calculate the amount of information (information entropy) required to fully identify the technical condition of a tractor applying each checkup set. Having such an assessment we may take a rational decision which checkup set to use in practice. The criterion for this evaluation will be based on the minimum amount of information required for the complete identification of the tractor technical condition. In this case it will be checkup set 3.

The presented example application of this method confirmed that the provided numerical scores for the informative value (information entropy) of checkup sets adequately describe the actual process for the determination of the tractor technical condition. A necessary precondition for an efficient application of the method is to create a set of potential checkups for a given signal as well as determine the probability of occurrence of individual damage/fault types.

### 6. Final conclusions

- 1. The method presented in this study provides a numerical evaluation for each of the potentially applicable checkup sets testing the technical condition of a tractor following the occurrence of a specific signal, based on the criterion of the amount of missing information (entropy). The results may be compared and the checkup set efficient in terms of its informative power may be selected, as that characterised by minimal entropy. This set will identify the technical condition of a tractor at the minimum number of checkups performed in an appropriate order.
- 2. The numerical measure of entropy for the checkup set is global in character and it accumulates information from tractor manufacturers, service stations and tractor operators. The

logic verification of the method and an example of its practical application indicate that it describes adequately the actual process generating checkup sets for the evaluation of the tractor technical condition. It is a universal method and may be applied in the case of other machines, provided an appropriate database is available.

3. The amount of missing information is calculated using probabilistic data, thus the recorded results may be referred to an adequately numerous set of tractors and then their practical use is efficient. Having a database on fault/damage and after performing appropriate calculations optimal checkup sets may be constructed, which will accumulate the experience of service mechanics and the specific character of tractor operation in a given region. An example of such a situation is presented in this study.

### References

- 1. Cieślikowski B. Proces diagnostyki układu hydrauliki siłowej mechanizmie obrotu pługa. Inżynieria Rolnicza 2009; 9(118): 23-27.
- 2. Grądzki R, Lindstedt P. Method of evaluation of technical object aptitude in environment of exploitation and service conditions. Eksploatacja i Niezawodnosc Maintenance and Reliability 2015; 17(1): 54-63, https://doi.org/10.17531/ein.2015.1.8.
- 3. Hebda M. Eksploatacja samochodów. Radom: Wydawnictwo Instytutu Technologii Eksploatacji, 2007.
- 4. Jasiulewicz-Kaczmarek M. Współczesne koncepcje utrzymania ruchu infrastruktury technologicznej przedsiębiorstwa. In: Koncepcje zarządzania systemami wytwórczymi. Poznań: Wydawca Instytut Inżynierii Zarządzania Politechniki Poznańskiej, 2005: 127-134.
- 5. Kaźmierczak J. Eksploatacja systemów technicznych. Gliwice: Wydawnictwo Politechniki Śląskiej, 2000.
- 6. Kołodziejski D., Jósko M. Wybrane problemy eksploatacyjne pojazdów i maszyn rolniczych w zakresie serwisowania. Journal of Research and Applications in Agricultural Engineering 2008; 53(2); 5-7.
- 7. Kosicka E, Kozłowski E, Mazurkiewicz D. The use of stationary tests for analysis of monitored residual processes. Eksploatacja i Niezawodnosc Maintenance and Reliability 2015; 17(4): 604-609, https://doi.org/10.17531/ein.2015.4.17.
- Kucharek M., Treichel W. Zastosowanie entropii informacji do oceny sieci monitoringu jakości wód podziemnych. Ochrona Środowiska 2006; 28, 3: 45-49.
- 9. Lazar I, Husar J. Verification of sequential patterns in production using information entropy. Tehnicki Vjesnik Technical Gazette 2013; 20(4): 669-676.
- 10. Legutko S. Eksploatacja maszyn. Poznań: Wydawnictwo Politechniki Poznańskiej, 2007.
- 11. Mieszała A, Zielińska E, Kordaś M, Rakoczy R. Zastosowanie entropii informacji do oceny stanu mieszaniny materiałów ziarnistych. Inż. Ap. Chem. 2013; 52, 4: 357-358.
- 12. Moubray J. Maintenance management a new paradigm. Maintenance, 1996; 11: 1.
- 13. Niziński S, Michalski R. Diagnostyka obiektów technicznych. Radom: Wydawnictwo i Zakład Poligrafii Instytutu Technologii Eksploatacji, 2002.
- 14. Niziński S, Liger K. Diagnostyka techniczna w systemach działania. Zagadnienia Eksploatacji Maszyn 2001; 3(127) 171-189.
- 15. Perez-Canales D, Alvarez-Ramirez J, Jauregui-Correa J C, Vela-Martinez L, Herrera-Rui G. Identification of dynamic instabilities in machining process using the approximate entropy method. International Journal of Machine Tools & Manufacture 2011; 51(6): 556-564, https://doi.org/10.1016/j.ijmachtools.2011.02.004.
- 16. Rzeźnik C, Rybacki P. A structural method for the evaluation of recyclability of agricultural machinery. Electronic Journal of Polish Agricultural Universities, Agricultural Engineering 2004; 7(2).
- 17. Sawczuk W. Application of vibroacoustic diagnostics to evaluation of wear of friction pads rail brake disc. Eksploatacja i Niezawodnosc Maintenance and Reliability 2016; 18(4): 565-571, https://doi.org/10.17531/ein.2016.4.11.
- Shannon C. E. A mathematical theory of communication. The Bell System Technical Journal 1948; 27: 379, https://doi.org/10.1002/j.1538-7305.1948.tb01338.x.
- Sowa A. Formal models of generating checkup sets for the technical condition evaluation of compound objects. Eksploatacja i Niezawodnosc
   Maintenance and Reliability 2014; 16(1): 150-157.
- Yan-Ting A, Jiao-Yue G, Cheng-Wei F, Jing T, Feng-Ling Z. Fusion information entropy method of rolling bearing fault diagnosis based on n-dimensional characteristic parameter distance. Mechanical Systems and Signal Processing 2017; 88: 123-136, https://doi.org/10.1016/j. ymssp.2016.11.019.

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### Marek PŁACZEK Łukasz PISZCZEK

### TESTING OF AN INDUSTRIAL ROBOT'S ACCURACY AND REPEATABILITY IN OFF AND ONLINE ENVIRONMENT

### BADANIA DOKŁADNOŚCI I POWTARZALNOŚCI POZYCJONOWANIA ROBOTA PRZEMYSŁOWEGO W ŚRODOWISKACH OFF I ONLINE\*

The paper discusses issues concerning the accuracy and repeatability tests of the positioning of the Kuka KR 16-2 industrial robot. The results of laboratory tests of an industrial robot, as well as a comparison of robot motion paths in the Robcad environment with the real robot motion paths are presented. In order to register movement paths in the laboratory conditions, the laser tracker Faro Vantage was used. Frequent necessity to correct programs of industrial robots created in the offline environment, is a results, among others, from the insufficient experience of people who carry out programming, the environment in which robots work and the parameters of the robots themselves, and therefore their accuracy and repeatability. It is connected with the extension of the start-up time and high costs. The work describes the measurement method and attempts to determine the influence of the type of route and motion parameters on the accuracy and repeatability of robot. The accuracy of mapping of simulated robot motion in a virtual environment was also verified.

*Keywords*: industrial robot, offline programming, online programming, positioning accuracy, repeatability of positioning.

W pracy omówiono zagadnienia dotyczące badań dokładności i powtarzalności pozycjonowania robota przemysłowego Kuka KR 16-2. Przedstawiono wyniki badań laboratoryjnych robota przemysłowego, a także dokonano porównania ścieżek ruchu robota symulowanego w środowisku Robcad ze ścieżkami ruchu robota rzeczywistego. W celu rejestracji ścieżek ruchu w warunkach laboratoryjnych zastosowano laserowy tracker Faro Vantage. Częsta konieczność poprawy programów robotów przemysłowych utworzonych w środowisku offline wiąże się z wydłużeniem czasu uruchomienia i dużymi kosztami. W artykule opisano metodę pomiarów oraz podjęto próbę określenia wpływu rodzaju ścieżki dojazdu do punktów pomiarowych i parametrów ruchu na dokładność i powtarzalność pozycjonowania robota. Zweryfikowano także dokładność odwzorowania ruchu robota symulowanego w środowisku wirtualnym.

*Slowa kluczowe*: robot przemysłowy, programowanie offline, programowanie online, dokładność pozycjonowania, powtarzalność pozycjonowania.

# 1. Accuracy, repeatability and programming of the movement of industrial robots

In modern industrial plants, robotic production cells and industrial robots are an extremely important element. In order to achieve the maximum efficiency and reliability of automated and robotic production lines, numerous scientific studies are carried out aimed at both the development of technical means themselves, as well as methods for their programming and exploitation [1, 2, 4, 5, 8, 10, 11, 13, 18]. In the case of industrial robots, the accuracy and repeatability of positioning are extremely important features affecting their operation [3, 6, 7, 12, 19, 21, 22, 26]. Therefore, research is conducted to improve the existing state of operation of this type of technical means, as well as to improve the measurement methods of their parameters [7, 9, 14-17, 20, 23, 24].

The accuracy of the manipulator is called his ability to reach a given point in the workspace. The basic method of determining accuracy errors in the positioning of an industrial robot is to measure angular or linear changes in individual links of its manipulator [19-21, 27, 28]. Due to the high cost and sensitivity for interferences of the used sensors, methods of direct measurement of the end effector are used less frequently. The factors of accuracy of positioning are influenced

by factors described more widely, among others, at work [21], such as positioning errors and trajectory rendering (for example due to deformations caused by the temperature, inaccuracies of control system signals or inertial forces). According to the PN-ISO 9283 standard, the accuracy of unidirectional positioning (AP) describes the deviation between the set position and the average value of the actual positions when reaching the set position from the same direction [26]. Repeatability of the manipulator is the ability to move the effector tip to the same, set point in space. The resolution of the control system is the first to influence the reproducibility of the manipulator.

Manipulators of industrial robots, currently used in industry, are characterized by very good reproducibility (RP) but not very good accuracy (AP). The measurement of the manipulator's position in the basic configuration is most often carried out by reading data from an encoder or resolver placed on the drive shaft of each axis. Robots can be equipped with additional measuring systems, but usually this option is additionally payable. Therefore, most often the position of the tool is calculated based on the measurement of angles or offsets of joints with additional consideration of the manipulator geometry and stiffness in relation to the mass it carries (tool load). The positioning accuracy is influed by the loose (wear) in joint connections, friction, transmission errors in gears, accuracy of the manipulator elements,

<sup>(\*)</sup> Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

finite mechanical stiffness, computational errors, work environment, elastic effects of components and mounting method, as well as many other static and dynamic factors.

Unfortunately, most of the above factors are subject to constant changes that cannot be predicted, which lead to the creation of differences between mathematical models and real characteristics. These differences can be tried to reduce by recalibrating mathematical models. Another method of improving accuracy can be the use of direct sensors at the end of the robot's mechanical interface, for example laser, inductive and vision sensors.

The most common method is programming robots through teaching. This method consists of discrete programming and continuous programming, which are very different by the character of teaching. Discrete programming is mainly used for manipulation of objects, for gluing and welding, and continuous programming is used where the movements of the robot must be smooth and continuous. This type of programming is very well suited to applications such as spray painting.

Currently, the offline robot programming method is being intensively developed. Its use gives the opportunity to significantly reduce costs, such as the cost of introduction of a new car model for production on the production line. In this method, the robot or its surroundings are very little needed for the programming process itself. It runs in a simulated 3D environment using Robcad, Delmia, Roboguide, Robot Studio, or Process Simulate software. The created virtual environment includes 3D models of devices from the existing technological line, the location of which is faithfully reproduced by 3D laser metrology, which allows for very accurate programming of robots, without the need for their physical participation. This action allows shortening the start-up time, reduces costs and allows for better refinement of the cycle time of the production line. A quick response is also possible when one of the models is incompatible, for example when the gripper is incompatible with the manipulation object at a given production stage. An additional advantage of this method is to reduce the risk of accidents on the assembly hall and increase the safety of robot operators. In offline programming, the precision of mapping of real objects as well as the robot itself is very important, taking into account the parameters of its work, including the accuracy and repeatability of positioning. Any errors in this regard are connected with the necessity to verify and improve the program developed in the real environment. This significantly reduces the advantages resulting from the offline robot programming method.

## 2. Research and methods to verify and improve the characteristics of industrial robot move

In this paper, attempts have been made to examine and verify the accuracy and repeatability of the positioning of an industrial robot simulated in a computer environment and a real robot. In order to carry out the tests, a laser measuring device was used. In [24], the authors also presented the concept of a method for measuring accuracy and repeatability using laser measuring technology. The use of detection based on laser interferometry, in the proposed technique of estimating positioning errors, aimed at improving the accuracy of an industrial robot, is also presented in [9]. This method is also presented in the works of other authors, in which precise, laser measuring devices are proposed as tools for positioning manipulators of industrial robots and machines [12, 14, 20].

Repeatability of the robot is limited mainly by the resolution of the position reading system, i.e. the smallest value that this system can recognize. Linear axes, so prismatic joints, usually have a better resolution than rotary axes (in a comparable price class), because the straight line drawn between two points is shorter than the corresponding arc. Spong and Vidyasagar [22] proved that in rotary axes errors are cumulated and are greater than in linear axes and result from stronger kinematic and dynamic couplings in these drives. This leads to increasing problems with controlling these axes. Another error hierarchy is described in [25]. It is as follows: position of the TCP (Tool Center Point), work piece position, joint position calibration, shoulder length and angular errors, shoulder flexibility, position encoder resolution, clearance, flexibility and misalignment, thermal deformation. The work [25] also discusses in detail the division and percentage share of the impact of individual error sources on the accuracy and repeatability of positioning. The presented data show that the most important impact on the accuracy of the robot is its incorrect calibration. Therefore, proper calibration is a condition that must be kept at the beginning of each work with an industrial robot. The ability to quickly and accurately calibrate is also an intensively developed issue in the aspect of building robots and their equipment [25].

In the article [26], the authors emphasize that the main disadvantage of programming robots in offline mode is their low accuracy. They indicate that industrial robots are mainly programmed using methods that only require good repeatability. As a result, little is done to improve parameters regarding the accuracy of positioning of industrial robots. The authors of the discussed study conducted experimental research on three modern robots in order to evaluate and compare their positioning accuracy. Based on measurements using a laser interferometry system, the accuracy errors of each robot were measured and the obtained results were compared. As it was demonstrated by the authors, analyzing the obtained results, it can be stated that in comparison to older robot models, the positioning accuracy of modern industrial robots can be very good, but achieving such accuracy depends on the correct calibration process.

Paper [21] presents the results of an experiment to assess the accuracy and repeatability of an articulated industrial robot. Six factors were analyzed, which are most often indicated as affecting the parameters of its work. The object investigated was the Fanue M16iL industrial robot. The planning, carrying out tests and analysis of the obtained results were described in detail. The verification of the accuracy and repeatability of the robot given by the manufacturer was also presented.

In work [16], the effectiveness of a measuring device designed for absolute calibration of small industrial robots was experimentally demonstrated. The proposed method of calibration is manual and labour-intensive, but its implementation takes less than an hour, and the cost of the measuring device used is less than 13,000 USD. As the authors of the study [16] indicate, the mean values and standard deviation of the absolute position and distance errors would then be about three times smaller. They proved that when the calibration time is not a problem, various improvements to the proposed solution are possible. Calibration, for example, can be repeated at different positions of the basic device. Different calibration models can also be used in different work zones. It is also possible to extend the proposed measurement system, and thus extend the range of measurable robot configurations four times. The authors suggest that the proposed calibration procedure has enormous potential as it is cheaper compared to the absolute calibration of small industrial robots. It can also be additionally used to confirm the accuracy of robot positioning. In another study [17], the authors proposed a 29-parameter calibration model and a procedure for the identification of the parameters of this model and measurements of an industrial robot ABB IRB 1600-6/1.45. This application makes it possible to improve the accuracy of the robot in terms of average and maximum position errors in the entire working area. The authors admit that the better effectiveness of the proposed method cannot be demonstrated juxtaposing with other calibration methods, including the method proposed by the robot manufacturer, however, the results obtained can be used as a reference point for comparative analysis.

Also in [15] the authors point out that one of the problems slowing down the development of offline programming is the low static and

dynamic accuracy of positioning of industrial robots. They indicate that the correct calibration of the robot improves the accuracy of its positioning and can also be used as a diagnostic tool in the manufacture and maintenance of robots. They present modelling techniques and performing robot calibration processes in offline programming mode using a three-dimensional measurement system. The authors indicate that the proposed measurement system is portable, accurate and not expensive. The discussed solution consists of a single CCD camera mounted on the robot's tool collar, which aims to measure the position of the end effector relative to the global coordinate system. In this photogrammetric model, radial distortion was taken into account. Scaling factors and image centres were obtained using an innovative technique with a multi-view approach. Achievable average accuracy was from 0.2 to 0.4 mm at distances from 600 to 1000 mm from the target, respectively in different camera orientations. The authors present the results of experiments carried out by two industrial robots ABB IRB-2400 and PUMA-500 in order to show the improvement of their accuracy using the proposed calibration system. Robots after calibration achieved better accuracy (three to six times than before calibration), and the solution proposed by the authors is quick, accurate and easy to configure.

An article [7] presents a simple and less expensive method of calibrating industrial robots using a vision system. In this system, the camera is rigidly attached to the robot's bunch, recording during the work the images of the calibration plate in the form of a chessboard. The algorithm of automatic image recognition and self-calibration of the camera is used without knowing the position of the calibration plate. The authors showed that the proposed method is simpler and cheaper than standard ones. It can also be used while the robot is operating in an unknown environment and in conditions that can significantly affect the operating parameters (high temperature or pressure). It can also be used in mobile robots.

Issues to improve the accuracy of positioning of industrial robots are discussed in paper [23], in which the authors examine the possibility of using the Leap Motion Controller for this purpose, which is typically used to manually control user gestures with declared accuracy below the millimetre. The article presents the study of the motion controller and the main emphasis is on the evaluation of its accuracy and repeatability. A test stand with the use of an industrial robot equipped with a reference pen to measure position accuracy up to 0.2 mm was developed. In the conducted experiments, a deviation was obtained between the desired position of the robot and its mean measured position, less than 0.2 mm in the case of static systems and 1.2 mm in the case of dynamic configurations.

The mentioned scientific publications are only selected items from the extensive, accessible literature on the subject. They confirm that there are numerous studies on both measurement methods and solutions that improve the accuracy and repeatability of positioning of industrial robots. In most studies, the correct calibration of an industrial robot is indicated as a factor significantly affecting these parameters. Various methods of measuring and improving the precision of mapping of programmed paths of industrial robot movements are also proposed. In this study, the authors also attempted to verify the accuracy and repeatability of the positioning of the selected industrial robot using a laser measuring system. Moreover, a comparison of the obtained values with the results obtained in a virtual simulation environment is presented, which is important in the offline programming of industrial robots.

The aim of the work carried out and discussed in the article was to propose a method for testing the accuracy and repeatability of industrial robot positioning in accordance with PN-EN 9283, using a standard tool that was used so far by people programming robots to measure a robotic cell and its modelling in a virtual environment. This topic is extremely important for people involved in programming industrial robots due to frequent discrepancies between the robot's motion path simulated in a virtual environment and the real robot motion path, performed on the basis of a program written in the offline environment. These discrepancies cause the necessity to make adjustments to programs before starting the work of robots and are associated with high time-consuming work, as well as with high costs.

## 3. Simulation and experimental tests of an industrial robot

This paper presents the results of simulation tests and laboratory measurements of a real object - the robot Kuka KR 16-2. The type of industrial robot under consideration is mainly used for welding tasks (it has a lifting capacity of 16 kg and its own weight of 235 kg).

In order to compare the results of offline and online programming, data generated in both the Robcad program and by the Faro Vantage laser tracker, used in measurements on the real object, were used. In the Robcad program was written, tested and loaded into the type of robot under consideration. In the simulation were used tools from groups:

- Motion that allows manipulating the simulated robot;
- Kuka KR C1 Spot, responsible for operating the Robot Controller Software (RCS) and entering information about individual points;
- Path Editor, where information about saved robot paths is stored;
- Placement Editor, responsible for the ability to move objects in a robotic cell.

In order to be able to use the Faro tracker for measurements during the conducted tests, it was necessary to properly determine the base (work object) and the Tool Center Point (TCP) point of the robot, because the points created by the robot are determined by the distance and rotation of the TCP system relative to the specified base system. The robot base was defined by measurements of two planes: the first one, in order to determine the height at which the point zero is located and direction of the Z axis and the second to determine the direction of the X axis. To facilitate the work and obtain maximum accuracy, the tracker was based on the so-called robot zero point. It is a factorydefined, fixed coordinate system, placed in the central part of the J1 axis, at ground level. The TCP system was defined by attaching to the robot's load an adapter with a strong magnet and a measuring probe, and then the robot reached random eight points. Next, the coordinates of each point indicated by the robot were entered into the Kuka Funke program, with the use of which TCP values were determined. These values were written in the memory of the real and simulated robots. The values that define the TCP system are its distances and rotations relative to the tool 0 system. It is a predefined coordinate system, located in the central part of the J6 axis, at the level of the robot bunch, constantly moving with it. After measuring the TCP value (in this case it is the central part of the probe's mirrors attached to the adapter), the values are stored in the robot's memory as tool 5 and from now both the adapter and the Faro measuring device must remain immobilized on their positions (adapter was immobilized on the robot's load with the glue). The probe can be detached from the adapter for the time the robot travels with the maximum speed between points, because the adapter is very accurate and does not introduce significant measurement errors. Fig. 1 shows the considered industrial robot simulated in the Robcad program together with the TCP and Toolframe coordinate systems.

The measurements were carried out in the ProPoint SP. Z O.O. SP. K. laboratory. The required measurement conditions were provided, as a rigid, reinforced concrete base, to which the tested industrial robot manipulator was attached. The rigid substrate does not introduce significant measurement errors by, for example, bending during the robot's work. The Faro Vantage tracker was placed two meters



Fig. 1. Location of coordinate systems of a simulated industrial robot in the Robcad program: TCP (marked in green) and the factory defined Toolframe coordinate system (marked in blue)

from the tested robot when it is in the Home position. According to the manufacturer's specification, the accuracy of measurements performed in this configuration, when measuring the linear distance, is 0.009 mm [28]. At the end of the robot's manipulator, a load and SMR (Spherically Mounted Retroreflector) probe with the adapter was mounted, attached to the robot's bunch. The room temperature during the tests was 22 degrees Celsius (according to PN-EN 9283, a temperature of 20 degrees Celsius +/- 2 degrees is required [27]). The robot was subjected to a forty-minute cycle of work on all axes before measurements, which ensured heating of drives and transmissions. The Faro tracker was immobilized in the correct position using glue. In addition, four adapters, identical to the adapter attached to the robot load, were used and were attached to stationary, metal points of the laboratory, such as a door frame. Using the base points created in this way, it was possible to re-base the measurement tracker in the event of its possible move during the tests. This operation also allows moving the tracker to a different location, because after it has been properly positioned, it is not necessary to re-determine the robot base for which measurements are made. According to the requirements, in order to ensure the reliability of measurements, they should be carried out with the full nominal load of the tested robot. Using data obtained from the Kuka Load program, the mass fixed on the J6 axis and the moments of inertia and force generated by it were determined. The load was made in the form of laser cut five steel discs with a diameter of 155 mm connected to each other which were attached to the robot's bunch using a developed adapter.

Tests that was carried out:

- accuracy of the robot, defined as the difference between the programmed and the actual coordinates of the TCP point,

- robot repeatability, that is the calculation of the sphere radius, in which the measuring points are contained during subsequent movements of the robot,

- path mapping, comparing the trajectory of the virtual robot simulated in the software and the trajectory of the real robot,

- emergency stop (E-STOP).

Guided by the recommendations included in the PN-EN 9283 standard, measuring cubes with different side lengths were determined, and the measuring points were placed in four vertices of these cubes, diagonally. The measuring plane created in this way is shown in Fig. 2 [27].

Fig. 3 and 4 show the robot in simulated and real environments, at measurement points selected from C4-C3-C6-C5 (Figure 2). This comparison allows specifying the robot's configuration and determining if it is the same in both environments. Analyzing the obtained results, it can be stated that the robot in the simulation achieves the same axis configurations as the robot in reality. These configurations



Fig. 2. Measuring plane determined by points located in the vertices of the cube in accordance with the PN-EN 9283 standard [27]



Fig. 3. Virtual and real robot at C4-C3-C6-C5 measurement points of the cube with 1000 mm side length, with tool rotation +20° in Y axis

occur in simulation in several different variants, so it was necessary to recognize what option to use in the case of a real robot. This is not a problem when programming using the RCS (Robot Controller Software) system, because then it is automatically selected or converted to the correct variant. Correct projection of the real robot in a virtual



Fig. 4. Virtual and real robot at C4-C3-C6-C5 measurement points of the cube with 1000 mm side length, with tool rotation +20° in the X and Y axes

environment was found. In both presented cases, the robot is correctly projected at all measuring points. The selected two robot configurations were presented during measurements carried out in a cube with a side of 1000 mm. In the first one, the tool rotation by the angle of + 20° in the Y axis (Fig. 3) and in the second the tool rotation by an angle of + 20° in the X and Y axes was applied. Despite the identical C5 point coordinates, the entered tool rotation in the X and Y axes caused a change of the robot's configuration and rotation of the J4 axis by 180° in relation to the robot's configuration with the tool rotation only in the Y-axis. Both cases, however, were faithfully reproduced by the robot simulated in a virtual environment.

### 4. Positioning accuracy tests

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The positioning accuracy tests at individual measurement points marked with AP were carried out in accordance with the guidelines of PN-EN 9283 [27]. The coordinates of the set position were specified in the robot program, while the coordinates of the position reached were read from the Faro tracker's indications. For calculations the equation was used [27]:

$$\Delta P_{\rm P} = \sqrt{\left(\overline{\mathbf{x}} - \mathbf{x}_{\rm c}\right)^2 + \left(\overline{\mathbf{y}} - \mathbf{y}_{\rm c}\right)^2 + \left(\overline{\mathbf{z}} - \mathbf{z}_{\rm c}\right)^2} , \qquad (1)$$

where:

$$\overline{\mathbf{x}} = \frac{1}{n} \sum_{j=1}^{n} \mathbf{x}_j , \qquad (2)$$

$$\overline{\mathbf{y}} = \frac{1}{n} \sum_{j=1}^{n} \mathbf{y}_j , \qquad (3)$$

$$\overline{z} = \frac{1}{n} \sum_{j=1}^{n} z_j .$$
<sup>(4)</sup>

The symbols  $\overline{x}$ ,  $\overline{y}$ ,  $\overline{z}$  indicate coordinates of the set of measurement points,  $x_c$ ,  $y_c$ ,  $z_c$  coordinates of the set position,  $x_j$ ,  $y_j$ ,  $z_j$  coordinates of the j<sup>th</sup> measured position.

A sample of results of the robot positioning accuracy test for cubes with sides length of 200, 600 and 1000 mm, without tool rotation, are shown in Fig. 5-7. According to the guidelines included in the PN-EN 9283 standard, 30 measurements were carried out. Due to the repetitive nature of the obtained results and to ensure the readability of their presentation, the results of ten randomly chosen measurements were presented. Fig. 8 presents average results of positioning accuracy measurements at four measuring points of cubes with sides' length of 200, 600 and 1000 mm. In individual measurements, points were achieved after different robot motion paths:

- without tool rotation,
- with tool rotation by an angle of  $+20^{\circ}$  in the Y axis,
- with tool rotation by an angle of  $+20^{\circ}$  in the X and Y axis,
- in the case of a cube with a side length of 1000 mm, additionally without the rotation of the tool, at speeds of 10% and 50% of the maximum speed.

In the case of a cube with a side length of 200 mm, the positioning errors were in individual points: C4 (APp1) 1.23 - 1.59 mm, C3 (APp2) 1.11 - 1.53 mm, C5 (APp3) 0.8 - 0.91 mm and C6 (APp4)



Fig. 5. Accuracy of positioning of the cube points with a side length of 200 mm, without tool rotation



Fig. 6. Accuracy of positioning of the cube points with 600 mm side length, without tool rotation



Fig. 7. Accuracy of positioning of cube points with 1000 mm side length, without tool rotation

0.74 - 1.1 mm. Significant fluctuations in the positioning accuracy were found in the case of the C4 point, which may be due to the fact that the robot was approaching this position from the Home point located in the centre of the measurement cube. The results of the positioning accuracy test for a cube with 600 mm side length showed the following positioning errors at individual points: C4 (APp1) 1.74 - 1.81 mm, C3 (APp2) 1.13 - 1.6 mm, C5 (APp3) 0, 87 - 1.22 mm and C6 (APp4) 0.54 - 0.77 mm. At point C6, the robot is therefore characterized by a very high positioning accuracy, which does not require the use of additional corrective measures in the event of application of the developed program in the industry. When measuring the positioning accuracy of the robot in a cube with a side length of 1000 mm, it was found at individual points the following positioning errors: C4 (APp1) 1.5 - 1.77 mm, C3 (APp2) 0.95 - 1.04 mm, C5 (APp3) 1.96 - 2.36 mm and C6 (APp4) 1.59 - 1.97 mm.

In the case of C5 and C6 points, a very large deviation from the set position was shown, and here the coordinates of the points will have to be corrected. In the case of a measuring cube with a side length of 1000 mm, additional measurements were made at the speed of movement of the robot limited to 10% and 50% of the maximum value, however, constant during individual tests. The purpose of this action was to check whether the limitation of the robot's travel speed limits



Fig. 8. The average values of robot positioning accuracy, for each paths, at individual measuring points

the deviation from the present position. The results of the test indicate the following positioning errors at individual points: C4 1.53 - 1.64 mm, C3 0.78 - 0.87 mm, C5 2.16 - 2.18 mm and C6 2 - 2.01 mm. On this basis, it can be stated that the change in the robot's speed does not have a significant effect on the difference in the value of deviations from the set position in individual tests. It was not noticed that the deviation values were clearly closer to zero as the robot's speed decreased in individual passes. The expected reduction in the positioning accuracy can be observed with the increase of the cube size and the complexity of the path only to cubes with sides of 200 and 600 mm. With larger dimensions of the measuring cube, the positioning accuracy of the robot is different in relation to the points of individual tracks and unpredictable. It is therefore necessary to take into account the occurrence of these errors, because they cannot be avoided, for example by means of program compensation.

### 5. Tests of repeatability of positioning

Reproducibility tests of the positioning of an industrial robot marked with the  $RP_l$  symbol were carried out in accordance with the guidelines of PN-EN 9283 [27]. The results were developed using data from positioning accuracy tests. Repeatability is defined as a sphere with a radius equal to the value of repeatability  $RP_l$  and a centre with coordinates calculated from the average coordinates of individual measurement points in accordance with the following relationships:

 $RP_1 = \overline{1} + 3S_1$ 

where:

(5)

$$\overline{l} = \frac{1}{n} \sum_{j=1}^{n} l_j , \qquad (6)$$

$$l_{j} = \sqrt{\left(x_{j} - \overline{x}\right)^{2} + \left(y_{j} - \overline{y}\right)^{2} + \left(z_{j} - \overline{z}\right)^{2}} , \qquad (7)$$

$$S_{l} = \sqrt{\frac{\sum_{j=1}^{n} (l_{j} - \overline{l})^{2}}{n-1}}$$
(8)

Fig. 9-11 show the selected results of calculating the repetition of the positioning of the considered robot, when reaching individual



Fig. 9. Repeatability of positioning of the cube points with a side length of 200 mm, with tool rotation +20° in X and Y axes

measurement points. The created spheres, in individual drawings, were scaled in relation to each other

Figure 12 summarizes the average results of the positioning repeatability test in four measurement points of cubes with sides' length of 200, 600 and 1000 mm.

- In individual measurements, points were achieved:
- without tool rotation,
- with tool rotation by an angle of  $+20^{\circ}$  to the Y axis,
- with tool rotation by an angle of  $+ 20^{\circ}$  relative to the X and Y axes,
- in the case of a cube with a side length of 1000 mm, additionally without the rotation of the tool at speeds of 10% and 50% of the maximum speed.

The results of the positioning repeatability test for a cube with a side length of 200 mm show errors at individual points: C4 0.12  $\pm$  0.03 mm, C3 0.055  $\pm$  0.015 mm, C5 0.035  $\pm$  0.015 mm and C6  $0.04 \pm 0.01$  mm. It should be noted that the sphere at point C4 has a clearly larger radius in relation to the other spheres. The highest value of positioning repeatability, for each of the measurement points, was obtained in the test with tool rotation at axes X and Y. In the case of a cube with a side length of 600 mm, positioning errors were found at individual points: C4 0.045  $\pm$  0.005 mm, C3 0.03  $\pm$  0.01 mm, C5  $0.03 \pm 0.01$  mm and C6  $0.035 \pm 0.005$  mm. The determined spheres of repeatability of positioning for the measuring cube with side length 600 mm are more even than the measuring cube with side length 200 mm. In addition to the uniformity of measurements, it should also be noted that their small values indicate very good robot repeatability. In the case of cubes with a side length of 1000 mm, repeatability errors were found at individual points: C4 0.055  $\pm$  0.015 mm, C3 0.055  $\pm$ 0.015 mm, C5 0.075  $\pm$  0.035 mm and C6 0.08  $\pm$  0.04 mm. Spheres have a large discrepancy between the values of repeatability at each of the measurement points. Therefore, it cannot be determined which of the points was achieved with the best reproducibility. As a result of the repeatability of positioning test with variable speed of travel, the following positioning repeat errors were shown in particular points: C4 0.09  $\pm$  0.01 mm, C3 0.035  $\pm$  0.005 mm, C5 0.045  $\pm$  0.015 mm and C6  $0.03 \pm 0.01$  mm. The results obtained during the tests with the reduced speed suggest that the low speed does not change the value of the positioning repeatability and it is not justified to reduce it to obtain better repeatability.

As it was observed, the robot positioning repeatability is varied at the measuring points of individual paths. On the basis of all tests, no specific trend of the robot's positioning repeatability can be demonstrated. In the case of the industrial robot under study, the obtained values of repeatability of positioning are not a significant problem when creating programs in offline mode, because the values of deviations are negligible in relation to the tasks for which the robot can be used (mainly welding).

## 6. Study of the mapping of the robot's motion path in real and virtual environments

The path mapping study aimed to determine how the movements of an industrial robot programmed in a virtual offline programming environment are reproduced in reality. For this purpose, the "TCP track" option was used in the Robcad program, by means of which it is possible to create points in the TCP location on the robot's motion path. To register the real robot's path, a Faro tracker was used. Due to the fact that the robot's movement did not follow the path perpendicular to the tracker, the probe had to be periodically moved towards the tracker (SMR viewing angle is 30°). The robot's travel speed has been reduced to 150 mm/min. After the measurements, the coordinates of the points, measured by the Faro tracker, were copied to the Robcad program. For this purpose, a macro program of Microsoft Excel



Fig. 10. Repeatability of positioning of the cube points with a side length of 600 mm, with tool rotation  $+20^{\circ}$  in X and Y axes



Fig. 11. Repeatability of positioning of the cube points with a side length of 1000 mm, with tool rotation  $+20^{\circ}$  in X and Y axes



Fig. 12. The average values of the positioning repeatability  $RP_l$  of each track at individual measuring points

was used, which recorded reference measuring points spaced apart by 10 mm.

The real robot track recorded in this way was compared at the created reference points with the paths generated in the Robcad program. In the first case, the registered course of the real robot path was compared with the simulated path in the "*default*" mode (normally supplied with the Robcad program), in the second simulation the Robot Controller Software (RCS) "Kuka\_KRC1\_Spot" was used.

Fig. 13 graphically presents the differences between the course of obtained paths in one of the planes in the virtual environment in the "default" mode (violet colour) and with the RCS tool (yellow colour). Fig. 14 and 15 show the deviations in individual axes of the path simulated in a virtual environment relative to the path measured on the real robot, respectively in the case of simulation in the "default" mode (Fig. 14) and using the RCS Kuka\_KRC1\_Spot tool (Fig. 15). On the other hand, Fig. 16 shows a graphical comparison of paths created by the Robcad program and the paths of the real robot movement with tool rotation  $+ 20^{\circ}$  in the X and Y axes. It is clearly visible that the real path (blue) coincides with the path created using the RCS tool (yellow), but significantly differs from the path created in the "default" mode (violet colour).



Fig. 13. Paths created by the Robcad program when moving from the Home position with the tool rotation + 20° in the X and Y axes: Violet colour - the path created in the "default" simulation mode, yellow - in the simulation mode with the RCS tool



Fig. 14. Path deviation with tool rotation  $+ 20^{\circ}$  in X and Y axes in Robcad in "default" mode relative to the path measured by the Faro tracker



Fig. 15. Path deviation with tool rotation + 20° in X and Y axes in the Robcad program with the RCS Kuka\_KRC1\_Spot tool relative to the path measured by the Faro tracker



Fig. 16. Comparison of paths created by the program Robcad and the real path with the rotation of the tool +20° in the X and Y axes. Paths: real - blue colour, simulated in the "default" mode - violet colour, simulated with the RCS tool - yellow colour

### 7. Summary

Programming robots in the offline environment depends to a large extent on the exact mapping of elements of their real environment as well as their distribution. Therefore, it is important that the measurements of objects in the real robot work environment are carried out carefully and accurately. It is also very important to determine the work object base and its TCP point. This task requires high precision. The experience and skills of the person responsible for the measurements play a key role in offline programming as well as the launch of the real robot.

When creating programs in the offline environment, it must also be taken into account some imperfections of the industrial robot, and therefore its accuracy and repeatability of positioning. As demonstrated during the tests, these are quantities that cannot be precisely predicted. The accuracy of modern industrial robots currently used in most production plants can be a significant problem for programmers. As it was shown, when measuring the accuracy of reaching the set measuring points, in the case of a cube with a side length of 1000 mm, one of the points was achieved with an error of 2.21 mm in relation to the set position. This value is unacceptable and needs to be corrected during online programming. It should be noted that this error will occur regardless of how well the program was prepared in the offline environment, or how accurately the robot's environment was measured and mapped in a virtual environment. Even the best-written offline program may turn out to be inadequate to the real world. It is extremely important that a person, who is responsible for programming a real robot in his work environment, verifies the points of his movement path, paying particular attention to those that are close to the elements of the environment or are process points in such operations, like gluing or welding. The introduced patch of the program developed offline will be maintained during the robot's work due to high repeatability, whose value in the worst case during the test was 0.15 mm. This ensures that the robot's position is achieved with the required precision.

An important element is also the use of appropriate software in the offline environment, because the real robot's motion paths can have serious deviations from programs created in this environment. This introduces a threat to the robotic cell equipment and can lead to collisions. The right software allows working offline, without worrying that the actual robot will move along paths significantly different than the robot in the simulation. When comparing the motion path of an industrial robot simulated in a 3D environment with real conditions, significant discrepancies were found when using standard software ("*default*" mode). They can be significantly reduced by using an additional Robot Controller Software tool offered for the Robcad system.

During the tests, the accuracy and repeatability of positioning of an industrial robot and precision of mapping of motion paths, developed during offline programming, by a real robot were verified. The presented measurement method also allows assessing the impact of such factors as its load or ambient temperature on these parameters of the robot's motion. This paper discusses the most important aspects of offline and online programming of industrial robots. In order to fully evaluate the precision of an industrial robot, one should also take into account additional parameters of its work, such as the mapping of rotation behaviour at process points, robot dynamics measurements, etc. These issues are the subject of further research and their results will be presented in subsequent works by the authors.

### References

- 1. Banaś W, Herbuś K, Kost G, Nierychlok A, Ociepka P, Reclik D. Simulation of the Stewart platform carried out using the Siemens NX and NI LabVIEW programs. Advanced Materials Research 2014; 837(1): 537-542.
- 2. Bocian M, Jamroziak K, Kulisiewicz M. An identification of nonlinear dissipative properties of constructional materials at dynamical impact loads conditions. Meccanica 2014; 49(8): 1955-1965, https://doi.org/10.1007/s11012-014-9931-z.
- 3. Brink J, Hinds B, Haney A. Robotics repeatability and accuracy: another approach. Texas Journal of Science 2004; 56 (2): 149–156.
- 4. Buchacz A, Płaczek M, Wróbel A. Modelling of passive vibration damping using piezoelectric transducers the mathematical model. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2014; 16 (2): 301–306.
- Cholewa A, Świder J, Zbilski A. Verification of forward kinematics of the numerical and analytical model of Fanuc AM100iB robot. IOP Conf. Ser.: Mater. Sci. Eng. 2016; 145(1): 052001, https://doi.org/10.1088/1757-899X/145/5/052001.
- 6. Conrad K L, Shiakolas P S, Yih T C. Robotic calibration issues: accuracy, repeatability and calibration. Proceedings of the 8th Mediterranean Conference on Control & Automation (MED 2000), Rio, Patras, GREECE, 17-19 July 2000.
- 7. Du G, Zhang P. Online robot calibration based on vision measurement. Robotics and Computer-Integrated Manufacturing 2013; 29 (1): 484–492, https://doi.org/10.1016/j.rcim.2013.05.003.
- 8. Dymarek A, Dzitkowski T, Herbuś K, Kost G, Ociepka P. Geometric analysis of motions exercised by the Stewart platform. Advanced Materials Research 2014; 837(1): 351-356.
- 9. Gürsel A, Bijan S. A systematic technique to estimate positioning errors for robot accuracy improvement using laser interferometry based sensing. Mechanism and Machine Theory 2005; 40 (8): 879–906, https://doi.org/10.1016/j.mechmachtheory.2004.12.012.
- Herbuś K, Kost G, Reclik D, Świder J. Integration of a virtual 3D model of a robot manipulator with its tangible model (phantom). Advanced Materials Research 2104; 837(1): 582-587.
- Jamroziak K, Bocian M, Kulisiewicz M. Energy consumption in mechanical systems using a certain nonlinear degenerate model. Journal of Theoretical and Applied Mechanics 2013; 51 (4): 827-835.
- 12. Kluz R, Trzepieciński T. The repeatability positioning analysis of the industrial robot arm. Assembly 2014; 34 (3): 285–295, https://doi. org/10.1108/AA-07-2013-070.
- Płaczek M. Conception of the system for traffic measurements based on piezoelectric foils. IOP Conf. Series: Materials Science and Engineering 2016; 145 (1): 042025, https://doi.org/10.1088/1757-899X/145/4/042025.
- Mayer J R, Parker R, Graham A. A Portable Instrument for 3-D Dynamic Robot Measurements Using Triangulation and Laser Tracking. IEEE Transactions on Robotics and Automation 1994; 10 (4): 504–516, https://doi.org/10.1109/70.313100.
- 15. Motta J M, Carvalho G C, McMaster R S. Robot calibration using a 3D vision-based measurement system with a single camera. Robotics and Computer Integrated Manufacturing 2001; 17 (1): 487–497, https://doi.org/10.1016/S0736-5845(01)00024-2.
- 16. Nubiola A, Bonev I A. Absolute robot calibration with a single telescoping ballbar. Precision Engineering 2014; 38 (1): 472–480, https://doi. org/10.1016/j.precisioneng.2014.01.001.

- 17. Nubiola A, Bonev IA. Absolute calibration of an ABB IRB 1600 robot using a laser tracker. Robotics and Computer-Integrated Manufacturing 2013; 29 (1): 236–245, https://doi.org/10.1016/j.rcim.2012.06.004.
- Płaczek M, Buchacz A, Wróbel A. Use of piezoelectric foils as tools for structural health monitoring of freight cars during exploitation. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2015; 17 (3): 443–449, https://doi.org/10.17531/ein.2015.3.16.
- Shiakolas P S, Conrad K L, Yih T C. On the accuracy, repeatability, and degree of influence of kinematics parameters for industrial robots. International Journal of Modelling and Simulation 2002; 22 (3): 1–10, https://doi.org/10.1080/02286203.2002.11442246.
- Shirinzadeh B, Teoh P L, Tian Y, Dalvand M M, Zhong Y, Liaw HC. Laser interferometry-based guidance methodology for high precision positioning of mechanisms and robots. Robotics and Computer-Integrated Manufacturing 2010; 26 (1): 74–82, https://doi.org/10.1016/j. rcim.2009.04.002.
- 21. Şirinterlikçi A, Tiryakioğlu M, Bird A, Harris A, Kweder K. Repeatability and accuracy of an industrial robot: laboratory experience for a design of experiments course. The Technology Interface Journal 2009; 9 (2): 1-10.
- 22. Spong M W, Vidyasagar M. Robot Dynamics and Control, Wiley, 1989.
- 23. Weichert F, Bachmann D, Rudak B, Fisseler D. Analysis of the Accuracy and Robustness of the Leap Motion Controller. Sensors 2013; 13(5): 6380-6393, https://doi.org/10.3390/s130506380.
- 24. Wiśniewski M. Proposed method for measuring the accuracy and repeatability of positioning of industrial robots in industrial conditions. Technologia i Automatyzacja Montazu 2014; 3 (1): 39–43 (In Polish).
- 25. Wiśniewski M. Research of precision and repeatability of industrial robots. Poznań University of Technology Publishing House, 2015, Poznań.
- 26. Young K, Pickin C G. Accuracy assessment of the modern industrial robot. Industrial Robot: An International Journal 2000; 27 (6): 427-436, https://doi.org/10.1108/01439910010378851.
- 27. PN-EN 9283:2003.
- 28. www.factory-metrology.faro.com/pl/kalibracja-robotow (Access: 06.08.2017).

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### NEW INSIGHTS INTO RELIABILITY PROBLEMS FOR SUPPLY CHAINS MANAGEMENT BASED ON CONVENTIONAL RELIABILITY MODEL

### NOWE SPOJRZENIE NA PROBLEMY ZWIĄZANE Z NIEZAWODNOŚCIĄ W ZARZĄDZANIU ŁAŃCUCHAMI DOSTAW Z PUNKTU WIDZENIA TRADYCYJNEGO MODELU NIEZAWODNOŚCI

The paper aims to find the relationship between conventional reliability and supply chain reliability, and introduce and adapt conventional reliability models to the field of supply chains, expanding the horizon of solving supply chain reliability problems. Based on a comprehensive literature review, the paper summarizes definitions of reliability in supply chain systems and presents reliability system structures and reliability indexes for supply chains. Relationship and differences between conventional reliability and supply chain reliability are shown. Illustrative examples such as the supply chain reliability problem in China are provided to show how to convert a supply chain reliability problem into a conventional reliability problem and then solve it using reliability techniques in conventional reliability.

*Keywords*: supply chain management, conventional reliability, supply chain reliability, reliability system structures, reliability indexes.

Celem artykułu jest znalezienie związku między niezawodnością w ujęciu tradycyjnym a niezawodnością łańcuchów dostaw, a także wprowadzenie i dostosowanie tradycyjnych modeli niezawodności do badań nad lańcuchami dostaw, co pozwoli na rozszerzenie możliwości rozwiązywania problemów dotyczących niezawodności tych ostatnich. W oparciu o obszerny przegląd literatury, w artykule przedstawiono pokrótce definicje niezawodności w systemach łańcucha dostaw oraz omówiono struktury systemów niezawodnościowych i wskaźniki niezawodności dla łańcuchów dostaw. Pokazano zależności i różnice między niezawodnością w rozumieniu tradycyjnym a niezawodnością łańcucha dostaw. Przedstawiono przykład problemu niezawodności łańcucha dostaw zaczerpnięty z realiów chińskich, ilustrujący jak można przekształcić problem niezawodności wa tradycyjny problem niezawodnościowych stosowanych w tradycyjnej analizie niezawodności.

*Slowa kluczowe*: zarządzanie łańcuchami dostaw, niezawodność w ujęciu tradycyjnym, niezawodność łańcucha dostaw, struktury systemu niezawodności, wskaźniki niezawodności.

### 1. Introduction

Supply chain systems are an integral part of most of modern business. As supply chain systems play a more critical role in business success and society, consequences of any unreliable behavior become increasingly severe in terms of cost, effort and time. Thus, high reliability is an essential attribute for a successful supply chain system in today's competitive environment. Numerous research efforts have been expended in studying supply chair reliability and related optimization problems.

To quantify reliability of supply chain systems, one research stream focuses on models that describe elements and activities of supply chain systems. For example, Bundschuh et al. built an integrated inbound supply chain model with many potential suppliers for products [7]. Wang et al. developed statistical spatial modeling techniques to approximate store location and capacity constraints [43]. Hsu & Li presented a supply chain network model to study the reliability evaluation [11]. Zhou et al. proposed hazard rate models for early detection of reliability problems [48]. Mettler et al. developed an intelligent supply chain design for non-hierarchical manufacturing networks [28]. Brumnik et al. presented a Markov chain model for estimating biometric system reliability in supply chain management [5]. Chen et al. built a common cause failure model between suppliers and

manufacturers [8]. Li et al. presented a supply disruption risk model to study impacts of decision sequence on reliability enhancement with supply disruption risks [18]. There are also other models such as the simulation model [39], economic model [9], stochastic model [40], link-capacity model [41], deterministic model [42], multi-stage supply chain model [3], supply chain operations reference (SCOR) model [13], network equilibrium model [44], and etc.

Reliability metrics are important in the study of supply chain reliability. Reliability metrics may be expressed as, for example, failure free operating time, failure rate, or mean time between specified events such as failure, replacement or overhaul [30]. Considerable research efforts have been devoted to evaluating system reliability using different reliability metrics [10, 12, 21, 45]. Thomas proposed a reliability interference theory method for quantifying reliability of contingency logistics systems [37]. Nieuwenhuyse & Vandaele estimated the delivery reliability for the lot splitting policy using an approximation method [26]. Liu et al. proposed an adjacency matrix of the meta-graph method to analyze structural reliability and integratedcapacity reliability [22]. Graph-theory based methods such as GOmethodology and petri nets were proposed for studying the supply chain reliability [19, 32]. Bottani & Rizzi studied selection problems of suppliers and products based on an adapted multi-criteria approach [4]. Lam & Ip adopted a spanning tree approach to get the reliability of a supply chain collaborative network [16]. Jia & Cui introduced the Copula method and studied the reliability of dependent supply chain systems [14]. Zhao et al. analyzed reliability of apparel supply chains based on the state space method [47]. Ohmori & Yoshimoto showed the management of supply chain disruption risks by the network reliability method [27]. Lukinskiy et al. proposed a formal conceptual apparatus for the supply chain reliability evaluation [23]. Other methods on supply chain reliability include, for example, the self-assessment method [6], uncertainty evaluation method [25], and Fuzzy theory based method [17].

Considerable research efforts have also been expended in the problem of reliability optimal design for supply chain management. To get superior results, analytical hierarchy analysis (AHA) and conjoint analysis are often used. AHA takes pair-wise comparisons while conjoint analysis uses rating or ranking methods [34]. There are also some research results based on other methods. For example, Quigley & Walls used Shapley's value to support trading of reliability metrics across a supply chain by minimizing the cost of the combined suppliers' reliability programmers [30]. Snyder & Daskin used mixed integer programming methods to minimize the increase in transportation costs under various failure scenarios [35]. Sohn & Choi developed a fuzzy quality function deployment model to design specification and improve the supply chain management reliability [36]. Other research works in reliability optimal design for supply chain management can be found in Balan et al. [2], Liao & Rittscher [20], Zaitzev & Bochazev [46], Madadi et al. [24], and Torabi et al. [38].

While many research efforts have been made for analyzing supply chain reliability, it still lacks a universal authority definition. Moreover, as structures of supply chain systems appear to be different from and more complicated than structures of conventional product-based systems, indexes and methods of supply chain reliability should be distinct from those of product-based reliability. This paper investigates the relationship and differences between the supply chain reliability and the conventional reliability, leading to some insights on how to model the supply chain reliability. Based on models and techniques of the conventional reliability. Based on the investigation, the paper also suggests some topics and directions that may be interesting in the further study.

Remaining parts of this paper are organized as follows. In Section 2, definitions of reliability for supply chain systems are summarized. In Section 3 we present reliability system structures for supply chain and some reliability indexes. Section 4 shows the relationship between conventional system reliability and supply chain reliability. Section 5 focuses on reliability problems in supply chains and discussions on their solution methodology. Illustrative examples are also provided to demonstrate the application of the proposed methodology. Section 6 are the applications, and some concluding remarks and extensions for further research are provided in Section 7.

### 2. Reliability definitions for supply chain systems

In general, reliability is defined as the probability that an item will perform a required function under stated environment and operational conditions for a stated period of time [1, 31]. Reliability in supply chains is developed from the conventional reliability concept. However, currently the supply chain reliability still lacks a universal authority definition. Below list some existing definitions for the supply chain reliability (SCR).

- The probability of the chain meeting mission requirements to provide the required supplies to the critical transfer points within the system [37].
- (2) The ability to meet the logistic performance expectations of customers [33].

- (3) The quality & reliability of products required by the customers [36].
- (4) Delivery reliability [15, 29]: measures the supplier's ability to predictably complete processes as promised. It is measured by perfect order fulfillment and demonstrates the degree to which a supplier is able to serve its customers within the promised delivery time.
- (5) Suppliers' ability to be completed in supply chain systems [49].

Some researchers also give definitions of service reliability [43] for supply chains. For a service reliability at location *x* it is defined as:

 $v(x) \equiv P\{\text{transportation time} < \text{specified time}\}$ .

While the supply-chain system reliability has been developed from the product-based system reliability, there exist both difference and similarity between them as demonstrated by the above definitions.

The adoption of the supply chain reliability definition is decided by the system model and needs of the system manager. It can be one of the definitions mentioned above when applicable, or some extension of one definition above based on the special feature of the considered system.

### 3. Reliability system structures for supply chains

There are some typical structures in conventional reliability, such as series system, parallel system, k-out-of-n. The supply chain systems can also be described by these structure models. As discussed below, the reliability factors of supply chain systems, in general, are more complicated than those of product-based reliability systems.

There are two major kinds of reliability models for supply chains: chain structure (Fig. 1) and network structure (Fig. 2).



Fig. 1. Chain structure



Fig. 2. Network structure

Regardless of the structure, a supply chain system is composed of nodes and links. Each node can be one of enterprises, suppliers or customers in the supply chain. Each link represents the relationship between enterprises, suppliers and customers. There are material flows, fund flows, information flows etc. in a supply chain. In general, a supply chain system is complicated in structure, linkage, flow, etc., which leads to the complexity of supply chain reliability problems.

The reliability of each node depends on factors on which customers focus. For example, the following definitions are related to different types of flows.

#### Material-flow-based consideration of nodes [37]:

- (1) P{supply > demand}
- (2) *P*{conformity supply > demand}
- (3) P{conformity supply > demand|within a specified time interval}

#### Fund-flow-based consideration of nodes:

- (1) *P*{money arrives before goods sent out}
- (2) P{paid unit cost  $\geq$  market unit price}

The node reliability can also be defined in terms of order form, quality of goods, delivery in time, storage etc.

The reliability of each link is related to factors, such as natural factors (road, weather, transportation reliability, transportation cost, etc.), business relationship, and political situation, etc.

### Relationship between conventional reliability and supply chain reliability

The differences between conventional reliability and supply chain reliability are listed as follows:

- (1) The reliability definitions are different at both the system and component levels.
- (2) Systems are different from network point of view; the focus of supply chain reliability may be flows of material, fund and information or combination of them. In most situations, the links/nodes have some capacity constraints, which is different from conventional reliability.
- (3) The independence is lost in supply chain reliability in general, which makes the reliability problems complex.

The similarities between conventional reliability and supply chain reliability are as follows:

- Most reliability techniques in conventional reliability can be used in supply chain reliability, from the point of view of product life cycle.
- (2) Most reliability indexes, such as reliability, availability, dependability, mean time to the first failure, etc., are applicable to supply chain systems.

## 5. Representative reliability problems in supply chains and illustrative examples

The SCR problems discussed in literature include: delivery reliability, structure reliability, performance reliability, reliability optimal design, importance of nodes in supply chain. Following are some examples to illustrate the SCR problems, and how to solve the supply chain reliability problems using reliability techniques in conventional reliability.

#### 5.1. Series supply chain system



Fig. 3. Series supply chain system

#### System description:

- (1) As Fig. 3 shows, the original supply amount is *Z*, and the final customer 4 needs the amount of goods *Y* (Fig. 3).
- (2) Suppliers 1, 2 and 3 take time durations  $T_i$  (i = 1, 2, 3) to transport the amount Z of some kind of goods successively. At the corresponding transportation stages there are successful rates  $p_i$  or loss rates (proportion)  $1 p_i$ ,  $0 \le p_i \le 1$ , (i = 1, 2, 3).

(3) All quantities  $Z, Y, T_1, T_1, T_3$  are non-negative random variables.  $T_1, T_1, T_3$  are dependent with each other and all  $p_i$  are independent with each other.

The supply chain system success criterion is: the conformity goods amount required by the final customer can be met within the specified time t.

#### Solution:

Based on the success criterion, the supply chain system reliability can be formulated as:

$$R(t) = P\{T_1 + T_2 + T_3 \le t \& p_1 p_2 p_3 Z \ge Y\}.$$

According to assumption (3):

$$R(t) = P\{T_1 + T_2 + T_3 \le t\} P\{p_1 p_2 p_3 Z \ge Y\},\$$

the dependence among  $T_1, T_1, T_3$  can be modeled using the copula method from the conventional reliability. A *N*-dimensional copula is a distribution function on  $[0,1]^N$  with standard uniform marginal distributions. Reserve the notation  $C(U) = C(u_1,...,u_N)$  for the multivariate distribution functions which are copulas. Hence *C* is a mapping of the form  $C:[0,1]^N \rightarrow [0,1]$  i.e. a mapping of the unit hypercube into the unit interval [50]. Specifically,  $C(F_1(t), F_2(t), F_3(t)) = F(T_1, T_1, T_3)$  is the Copula of  $T_1, T_1, T_3$ , and the  $\partial^n C(u, u, u_1)$ 

density Copula function is  $c(F_1(t), F_2(t), F_3(t)) = \frac{\partial^n C(u_1, u_2, u_3)}{\partial u_1 \partial u_2 \partial u_3}$ .

Thus the reliability of the example supply chair system is evaluated as:

$$R(t) = P\{T_1 + T_2 + T_3 \le t\} P\{p_1 p_2 p_3 Z \ge Y\}$$
  
=  $C(F_1(t), F_2(t), F_3(t)) \int_0^\infty [1 - F_Z(\frac{y}{p_1 p_2 p_3})] dG_Y(y).$  (1)

The mean time to the first failure of this example supply chain system is:

$$MTTF = \int_{0}^{\infty} R(t)dt$$
  
= 
$$\int_{0}^{\infty} \left\{ C(F_1(t), F_2(t), F_3(t)) \int_{0}^{\infty} [1 - F_Z(\frac{y}{p_1 p_2 p_3})] dG_Y(y) \right\} dt.$$
(2)

If we assume that the successful rates at corresponding stages are related to the corresponding transportation durations, then the situation becomes more difficult.

For example:

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$$p_i(t) = \begin{cases} c_i, & t \le t_i; \ 0 < c_i < 1, \\ 1, & \text{otherwise.} \end{cases}, \text{ or } p_i(t) = \begin{cases} a_i t, & t \le t_i; \\ 1, & \text{otherwise.} \end{cases}, \ i = 1, 2, 3.$$

In this case, we have:

$$R(t) = P\{T_1 + T_2 + T_3 \le t \& p_1 p_2 p_3 Z \ge Y\}$$
  
= 
$$\iiint_{u_1 + u_2 + u_3 \le t} \{ [\int_{0}^{\infty} (1 - F_Z(\frac{y}{p_1(u_1)p_2(u_2)p_3(u_3)})) dG_Y(y)] \varepsilon(F_1(t), F_2(t), F_3(t)) du_1 u_2 u_3.$$
  
(3)

It is clear that when the transportation successful rates depend on the transportation durations, there is an optimal problem in which the suppliers should choose the optimal transportation durations to make the supply chain reliability maximal.

### 6. Applications

China has established a developed logistics network system. It is important to study the reliability of the system because any reliability related problems could result in certain serious consequence, such as significant damage to property or inconvenience for people's life. Consider a supple chain system illustrated in Fig. 4. The suppliers are in Guangzhou, Shenzhen and Shanghai and they supply the goods to Beijing. Once a supplier cannot supply enough material to the factory, the supplier is in the failed state. The supply chain system is in the working state if and only if at least 2 suppliers are in the working state.



Fig. 4. A supply chain system in mainlan China

The problem can be converted to a conventional reliability problem, particularly, a 2-out-of-3: G reliability system. The state of the system is the number of the failed suppliers. For a k-out-of-n: G system, if the n suppliers are independent and identically distributed, then the reliability of the supply chain is:

$$R_{k/n}^{I}(t) = \sum_{j=k}^{n} C_{n}^{j} P\{X_{j+1}, \dots, X_{n} \le t \le X_{1}, \dots, X_{j}\}$$
$$= \sum_{i=k}^{n} C_{n}^{j} R^{j}(t) (1 - R(t))^{n-j}.$$

Let  $X_1, X_2, X_3$  denote the lifetime of the 3 suppliers in Guangzhou, Shenzhen and Shanghai, respectively. All the suppliers are in good states in the beginning. Suppose the functions of  $X_1$ ,  $X_2$  and  $X_3$ are  $F_1 = 1 - e^{-t}$ ,  $F_2 = 1 - e^{-2t}$  and  $F_2 = 1 - e^{-3t}$ , respectively. Then the reliability of the example system is:

$$R_{2/3}^{I}(t) = e^{-3t} + e^{-4t} + e^{-5t} - 2e^{-6t}.$$
 (4)

If the suppliers are dependent with each other, then we apply the copula method from the conventional reliability to model the dependence among the suppliers.

First we calculate the reliability of a dependent k-out-of-n: G system. There are j suppliers randomly chosen from  $X_1, X_2, ..., X_n$ in the m-th and let  $X_m^1, ..., X_m^j$  denote the lifetime of them, where  $m = 1, 2, ..., C_n^j$ . The distributions of  $X_m^1, ..., X_m^j$  are  $F_m^1(t), ..., F_m^j(t)$ respectively. Their copula of  $X_m^1, ..., X_m^j$  is  $C_m^j(F_m^1, ..., F_m^j)$ . The remain parts' lifetime of the n suppliers are denoted by  $Y_m^1, ..., Y_m^{n-j}$ and their copula is  $C_m^{*n-j}(F_m^{*1}(t), ..., F_m^{*n-j}(t))$ , shorted as  $C_m^{*n-j}(t)$ .

For  $X_n^{(\min)} = \min(X_1, X_2, \dots, X_n)$ , the reliability of  $X_n^{(\min)}$  is:

$$R_{\min}(\min(X_1, X_2, \dots, X_n))$$
  
=  $P(\min(X_1, X_2, \dots, X_n) > t) = P(X_1 > t, \dots, X_n > t) = \sum \operatorname{sgn}(F) C_n(F)$ 

where sgn(F) is 1 if *n* is even, and -1 if *n* is odd.

For  $X_{n}^{(\max)} = \max(X_1, X_2, \dots, X_n)$ , the reliability is:

$$R_{\max}(X_1, X_2, ..., X_n)$$
  
=  $P(\max(X_1, X_2, ..., X_n) > t) = 1 - P(\max(X_1, X_2, ..., X_n) < t)$   
=  $1 - P(X_1 < t, ..., X_n < t) = 1 - C(X_1, X_2, ..., X_n) = 1 - C_n$ 

For a k-out-of-n: G system, if the m-th j parts in the n components are in working state, and the others are failed, then the reliability is:

$$\begin{split} R_m^j(t) &= P\{\max(Y_m^1, \dots, Y_m^{n-j}) \le t, \ \min(X_m^1, \dots, X_m^j) > t\} \\ &= P\{\max(Y_m^1, \dots, Y_m^{n-j}) \le t\} - P\{\max(Y_m^1, \dots, Y_m^{n-j}) \le t, \ \min(X_m^1, \dots, X_m^j) \le t\} \\ &= C_m^{*n-j}(t) - C(\max, \min(C_m^{*n-j}(t), \prod_j R_S^{-}(t)). \end{split}$$

So the reliability of a k -out-of-n : G system is:

$$R_{k/n} = \sum_{j=k}^{n} \sum_{m=1}^{C_n^j} \{R_m^j(t)\}.$$
 (5)

Then for the 2-out-of-3: G supply chain system, take three-dimensional Clayton copula  $C_1^{Cl}(u_1, u_2, u_3) = (u_1^{-1} + u_2^{-1} + u_3^{-1} - 2)^{-1}$  to model the dependence among the suppliers. Based on Eq. (5), the reliability of the supply chain system is:

$$R_{2/3}^{D}(t) = e^{-2t} - \left\{ (1 - e^{-t})^{-1} + (1 - e^{-3t})^{-1} - 1 \right\}^{-1} + \left\{ (1 - e^{-t})^{-1} + (1 - e^{-2t})^{-1} + (1 - e^{-3t})^{-1} - 2 \right\}^{-1}.$$
(6)

Based on Eq. (4) and (6), curves of the reliability for the dependent supply chain system  $R_{2/3}^D(t)$  and independent supply chain system  $R_{2/3}^I(t)$  are shown in Fig. 5.



So for the supply chain shown in Fig. 4, the reliability of the supply chain when the three suppliers are independent is shown as the curve  $R_{2/3}^{I}(t)$ , and is shown as the curve  $R_{2/3}^{D}(t)$  when they are dependent. In the beginning, the reliability when the suppliers are dependent is lower than that when they are independent, while after sometime t, the dependent case is higher.

### 7. Conclusion and further research

Supply chain management raises some new problems in the reliability discipline, which are generally more difficult than the problems we faced in the conventional product-based reliability problems. As demonstrated through examples, techniques and methods in the conventional reliability can be adapted to solve the supply chain reliability problems. We try to find the relationship between conventional reliability and supply chain reliability, and introduce and adapt conventional reliability models to the field of supply chain. The paper summarizes definitions of reliability in supply chain systems and presents reliability system structures and reliability indexes for supply chains. Relationship and differences between conventional reliability and supply chain reliability are shown. The following topics or directions may be interesting for further study:

(1) The development of new supply chain reliability models, including node models and link models.

- (2) A universal framework or guideline for supply chain reliability
- (3) Availability and dependability definition and modeling in supply chain systems.
- (4) Modeling reliability for various supply chain systems, such as contingency operation supply chain, industry product supply chain, food supply chain, etc.
- (5) Expanding the conventional reliability thinking, technique and methods to analyze the supply chain reliability.

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### References

- 1. AS/NZS ISO 8402:1994 Quality management and quality assurance Vocabulary standard. Australian/New Zealand Standards, 1994.
- Balan S, Vrat P, Kumar P. A strategic decision model for the justification of supply chain as a means to improve national development index. International Journal of Technology Management 2007; 40(1-3): 69-86, https://doi.org/10.1504/IJTM.2007.013527.
- 3. Beamon B M. Supply chain design and analysis: Models and methods. International Journal of Production Economics 1998; 55(3): 281-294, https://doi.org/10.1016/S0925-5273(98)00079-6.
- 4. Bottani E, Rizzi A. An adapted multi-criteria approach to suppliers and products selection—An application oriented to lead-time reduction. International Journal of Production Economics 2008; 111(2): 763-781, https://doi.org/10.1016/j.ijpe.2007.03.012.
- 5. Brumnik R, Iztok P, Mojca F P. Markov Chains Modelling for Biometric System Reliability Estimations in Supply Chain Management. Sensor Letters 2013; 11(2): 377-383, https://doi.org/10.1166/sl.2013.2133.
- 6. Bueno-Solano A, Cedillo-Campos M G, Cantú J M V. Reliability of the supply chain: method of self-assessment as a first step to building resilient systems. International Journal of Combinatorial Optimization Problems and Informatics 2016; 7(1): 3-9.
- 7. Bundschuh M, Klabjan D, Thurston D L. Modeling robust and reliable supply chains. Optimization Online e-print, 2003.
- 8. Chen G, Sun X, Hu H, et al. Research on modeling and algorithm of supply chain's reliability based on CCFSM. Journal of Coastal Research 2015; 73(sp1): 99-103, https://doi.org/10.2112/SI73-018.1.
- Christy D P, Grout J R. Safeguarding supply chain relationships. International Journal of Production Economics 1994; 36(3): 233-242, https://doi.org/10.1016/0925-5273(94)00024-7.
- Gurnani H, Shi M. A bargaining model for a first-time interaction under asymmetric beliefs of supply reliability. Management Science 2006; 52(6): 865-880, https://doi.org/10.1287/mnsc.1050.0498.
- 11. Hsu C I, Li H C. Reliability evaluation and adjustment of supply chain network design with demand fluctuations. International Journal of Production Economics 2011; 132(1): 131-145, https://doi.org/10.1016/j.ijpe.2011.03.020.
- 12. Huan S H, Sheoran S K, Wang G. A review and analysis of supply chain operations reference (SCOR) model. Supply Chain Management: An International Journal 2004; 9(1): 23-29, https://doi.org/10.1108/13598540410517557.
- Huang S H, Sheoran S K, Keskar H. Computer-assisted supply chain configuration based on supply chain operations reference (SCOR) model. Computers & Industrial Engineering 2005; 48(2): 377-394, https://doi.org/10.1016/j.cie.2005.01.001.
- 14. Jia X, Cui L. Reliability research of k-out-of-n: G supply chain system based on copula. Communications in Statistics-Theory and Methods 2012; 41(21): 4023-4033, https://doi.org/10.1080/03610926.2012.707736.
- Karpak B, Kumcu E, Kasuganti R. An application of visual interactive goal programming: a case in vendor selection decisions. Journal of Multicriteria Decision Analysis 1999; 8(2): 93-105, https://doi.org/10.1002/(SICI)1099-1360(199903)8:2<93::AID-MCDA235>3.0.CO;2-#.
- 16. Lam C Y, Ip W H. An improved spanning tree approach for the reliability analysis of supply chain collaborative network. Enterprise Information Systems 2012; 6(4): 405-418, https://doi.org/10.1080/17517575.2012.673236.
- 17. Lan T, Shen F J. Research on Reliability of Supply Chain Using Fuzzy Theory. International Journal of Trade, Economics and Finance 2016; 7(3): 62-66, https://doi.org/10.18178/ijtef.2016.7.3.500.
- Li,G, Zhang L J, Guan X, Zheng J J. Impact of decision sequence on reliability enhancement with supply disruption risks. Transportation Research. Part E, Logistics & Transportation Review 2016; 90(1): 25–38, https://doi.org/10.1016/j.tre.2015.09.008.
- 19. Li G, Zhang L, Guan X, et al. Impact of decision sequence on reliability enhancement with supply disruption risks. Transportation Research Part E: Logistics and Transportation Review 2016; 90: 25-38, https://doi.org/10.1016/j.tre.2015.09.008.
- 20. Liao Z, Rittscher J. A multi-objective supplier selection model under stochastic demand conditions. International Journal of Production Economics 2007; 105(1): 150-159, https://doi.org/10.1016/j.ijpe.2006.03.001.
- 21. Lin Y K. System reliability evaluation for a multistate supply chain network with failure nodes using minimal paths. IEEE Transactions on Reliability 2009; 58(1): 34-40, https://doi.org/10.1109/TR.2008.2011660.
- 22. Liu J, Li J, Zhao J. The research on supply chain reliability based on meta-graphs. Control and Automation, 2003. ICCA'03. Proceedings. 4th International Conference on. IEEE 2003; 849-853.
- 23. Lukinskiy V, Lukinskiy V, Churilov R. Problems of the supply chain reliability evaluation. Transport and Telecommunication Journal 2014; 15(2): 120-129, https://doi.org/10.2478/ttj-2014-0011.

- 24. Madadi A R, Kurz M E, Mason S J, et al. Supply chain design under quality disruptions and tainted materials delivery. Transportation Research Part E: Logistics and Transportation Review 2014; 67: 105-123, https://doi.org/10.1016/j.tre.2014.04.006.
- 25. Miao X, Yu B, Xi B. The uncertainty evaluation method of supply chain reliability. Transport 2009; 24(4): 296-300, https://doi. org/10.3846/1648-4142.2009.24.296-300.
- 26. Van Nieuwenhuyse I, Vandaele N. The impact of delivery lot splitting on delivery reliability in a two-stage supply chain. International Journal of Production Economics 2006; 104(2): 694-708, https://doi.org/10.1016/j.ijpe.2005.05.023.
- Ohmori S, Yoshimoto K. A framework of managing supply chain disruption risks using network reliability. Industrial Engineering and Management Systems 2013; 12(2): 103-111, https://doi.org/10.7232/iems.2013.12.2.103.
- 28. Mettler T, Pinto R, Raber D. An intelligent supply chain design for improving delivery reliability. International Journal of Information Systems and Supply Chain Management (IJISSCM) 2012; 5(2): 1-20, https://doi.org/10.4018/jisscm.2012040101.
- 29. Pokharel S. A two objective model for decision making in a supply chain. International Journal of Production Economics 2008; 111(2): 378-388, https://doi.org/10.1016/j.ijpe.2007.01.006.
- Quigley J, Walls L. Trading reliability targets within a supply chain using Shapley's value. Reliability Engineering & System Safety 2007; 92(10): 1448-1457, https://doi.org/10.1016/j.ress.2006.09.019.
- 31. Rausand M, Arnljot H Ã. System reliability theory: models, statistical methods, and applications. John Wiley & Sons, 2004.
- 32. Ren X L, Zhang G B. Reliability analysis of supply chain based on GO methodology. Applied Mechanics and Materials. Trans Tech Publications 2010; 34: 387-392.
- 33. Warburton R D H. An exact analytical solution to the production inventory control problem. International Journal of Production Economics 2004; 92(1): 81-96, https://doi.org/10.1016/j.ijpe.2003.09.014.
- 34. Saaty, T L. The analytical hierarchy process. Pittsburgh, RWS Publications, 1990.
- 35. Snyder L V, Daskin M S. Reliability models for facility location: the expected failure cost case. Transportation Science 2005; 39(3): 400-416, https://doi.org/10.1287/trsc.1040.0107.
- Sohn S Y, Choi I S. Fuzzy QFD for supply chain management with reliability consideration. Reliability Engineering & System Safety 2001; 72(3): 327-334, https://doi.org/10.1016/S0951-8320(01)00022-9.
- 37. Thomas M U. Supply chain reliability for contingency operations. Reliability and Maintainability Symposium, 2002. Proceedings. Annual. IEEE 2002; 61-67.
- Torabi S A, Baghersad M, Mansouri S A. Resilient supplier selection and order allocation under operational and disruption risks. Transportation Research Part E: Logistics and Transportation Review 2015; 79: 22-48, https://doi.org/10.1016/j.tre.2015.03.005.
- 39. Towill D R. Supply chain dynamics. International Journal of Computer Integrated Manufacturing 1991; 4(4): 197-208, https://doi. org/10.1080/09511929108944496.
- Tzafestas S, Kapsiotis G. Coordinated control of manufacturing/supply chains using multi-level techniques. Computer Integrated Manufacturing Systems 1994; 7(3): 206-212, https://doi.org/10.1016/0951-5240(94)90039-6.
- 41. Varshney P K, Joshi A R, Chang P L. Reliability modeling and performance evaluation of variable link-capacity networks. IEEE Transactions on Reliability 1994; 43(3): 378-382, https://doi.org/10.1109/24.326429.
- 42. Voudouris V T. Mathematical programming techniques to debottleneck the supply chain of fine chemical industries. Computers & Chemical Engineering 1996; 20: S1269-S1274, https://doi.org/10.1016/0098-1354(96)00219-0.
- 43. Wang N, Lu J C, Kvam P. Reliability modeling in spatially distributed logistics systems. IEEE Transactions on Reliability 2006; 55(3): 525-534, https://doi.org/10.1109/TR.2006.879603.
- 44. Yamada T, Imai K, Nakamura T, et al. A supply chain-transport supernetwork equilibrium model with the behaviour of freight carriers. Transportation Research Part E: Logistics and Transportation Review 2011; 47(6): 887-907, https://doi.org/10.1016/j.tre.2011.05.009.
- 45. Ye X, Zhang J, Liu Y, et al. Study on the measurement of international knowledge flow based on the patent citation network. International Journal of Technology Management 2015; 69(3-4): 229-245, https://doi.org/10.1504/IJTM.2015.072971.
- 46. Zaitzev, E I, Bochazev, A A. Optimizing supply-planning in multi-level network structures in the light of reliability. Logistics and Supply Chain Management 2010; 2 (37).
- 47. Zhao X H, Zhu Z T, Liu W H, et al. Research on Reliability of Apparel Supply Chain Based on State Space. Advanced Materials Research. Trans Tech Publications 2013; 821: 815-818.
- 48. Zhou C, Chinnam R B, Korostelev A. Hazard rate models for early detection of reliability problems using information from warranty databases and upstream supply chain. International Journal of Production Economics 2012; 139(1): 180-195, https://doi.org/10.1016/j.ijpe.2012.04.007.
- Shen Z J M. A profit-maximizing supply chain network design model with demand choice flexibility. Operations Research Letters 2006; 34(6): 673-682, https://doi.org/10.1016/j.orl.2005.10.006.
- 50. Nelsen R. An Introduction to Copulas. Springer-Verlag, New York 1999, https://doi.org/10.1007/978-1-4757-3076-0.

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### **EVALUATION ON GAS SUPPLY RELIABILITY OF URBAN GAS PIPELINE NETWORK**

### OCENA NIEZAWODNOŚCI DOSTAW GAZU W MIEJSKIEJ SIECI GAZOWEJ

As one of the lifeline projects, an urban gas network is a complex system, as it requires maintenance of the supply capacity when any single pipeline is isolated due to failure. For such a system, its reliability needs to be evaluated. Considering that existing structural reliability and hydraulic reliability analyses reflect different aspects of the working conditions of an urban gas network, system reliability theory is employed to explain that only the gas supply reliability can achieve a comprehensive evaluation of the work capacity of the entire urban gas network, as it takes into account the combined influence of the structural reliability and hydraulic reliability. To calculate the parameters in the gas supply reliability evaluation, such as pipeline failure rate, flow reduction in the gas network under different failure conditions, etc., some research achievements in the field of structural reliability and hydraulic reliability are fully utilized. Then, the detailed calculation procedures of these parameters are given to evaluate the gas supply reliability in terms of operational and practical considerations. Finally, using an example of a simple double-loop gas network, the detailed process of the gas supply reliability evaluation of an urban gas network is described, and the feasibility of this evaluation method is also illustrated.

*Keywords*: urban gas network; gas supply reliability; failure condition; flow reduction; pipeline failure; failure rate.

Miejska sieć gazowa – jeden z kluczowych elementów infrastruktury miasta – stanowi złożony system, ponieważ wymaga utrzymania zdolności przesyłowej gdy przepływ gazu w jednym z rurociągów zostaje zamknięty w wyniku awarii. W przypadku tego rodzaju systemów, konieczna jest ocena niezawodności. Biorąc pod uwagę, iż dostępne w literaturze analizy niezawodności konstrukcyjnej i niezawodności hydraulicznej odzwierciedlają różne aspekty warunków pracy miejskiej sieci gazowej, nie dają one pełnego obrazu niezawodności systemu jako całości. W artykule wykorzystano teorię niezawodności systemów, która pokazuje, że jedynie ocena niezawodności dostaw gazu stanowić może kompleksową ocenę wydajności pracy całej miejskiej sieci gazowej, ponieważ uwzględnia ona zarówno wpływ niezawodności konstrukcji jak i niezawodności hydraulicznej sieci. W pracy wykorzystano dotychczasowe obserwacje badawcze dotyczące oceny niezawodności konstrukcyjnej i niezawodności hydraulicznej sieci gazowej gazu w sieci gazowej w różnych warunkach uszkodzeń, itp. Następnie, podano szczegółowe procedury obliczania tych parametrów w celu oceny niezawodności przesyłowej sieci gazowej pod kątem eksploatacyjnym i praktycznym. Na koniec, na przykładzie prostej sieci gazowej składającej się z dwóch pętli, opisano szczegółowy proces oceny niezawodności dostaw gazu w miejskiej sieci gazowej i zilustrowano możliwość wykorzystania proponowanej metody.

*Słowa kluczowe*: miejska sieć gazowa; niezawodność dostaw gazu; warunki uszkodzenia; ograniczenie przepływu; uszkodzenie gazociągu; intensywność uszkodzeń.

### 1. Introduction

As one of the lifeline projects of an urban area, an urban gas network is a form of a municipal utilities infrastructure. The main function of urban gas networks is to transmit qualified natural gas and distribute it to the residential, commercial and industrial gas users for satisfying their gas demands. An urban gas network is a complex system and is often configured as multiple loops to ensure stability in maintaining a certain supply capacity when any single pipeline is isolated due to failure. For such a system, its reliability needs to be studied [1-3].

Existing reliability analyses of urban gas networks mainly include the structural reliability and hydraulic reliability of two branches. The former, from a mechanics point of view, focuses on the research of the probability of structural integrity of each pipeline unit and a whole network, without considering the influence of hydraulic conditions [4-7]. On the contrary, the latter, from a hydraulics point of view, focuses on whether the network hydraulic regime can satisfy the design requirements for pressure and flow under all possible conditions, especially when any single pipeline is isolated for repair due to failure [8,9]. In fact, the failure of any pipeline is a random probability event, that is, the hydraulic reliability analysis of urban gas networks also ignores the influence of the failure probability of any pipeline.

Structural reliability and hydraulic reliability analyses offer different perspectives and reflect different aspects of the working conditions of an urban gas network; furthermore, both of their research routes and conclusions are independent of each other, although there may be some intrinsic linkages between the two. Based on the above considerations, the system reliability theory is employed to explain that only the gas supply reliability can achieve a comprehensive evaluation of the working capacity of an urban gas network [10]. Furthermore, some research achievements in the field of structural reliability and hydraulic reliability are fully utilized to calculate the parameters in the gas supply reliability evaluation of urban gas networks.

#### 2. Gas supply reliability of urban gas networks

According to the code of GB 50153-2008 "Unified standard for reliability design of engineering structures" in China, the reliability is defined as a type of "capacity" that the product completes the required functions in the specified condition and time interval. The product here refers to any system, equipment or component.

An urban gas network consists of numerous pipelines, valves, and other non-pipe elements. The "capacity" of an urban gas network to complete the "required functions" mainly refers to its supply natural gas capacity. The ideal service life and supply capacity of each urban gas network have been determined in the network planning and design stage. Thus, the gas supply reliability of urban gas networks can be defined as within the design service life, the capacity to transmit qualified natural gas and safely distribute it to the residential, commercial and industrial gas users [3, 10, 11]. The qualified natural gas here means that the pressure and flow of the natural gas supplied by urban gas networks should satisfy the user demands in the given design conditions.

For any urban gas network, only through strict design, construction, acceptance and other necessary procedures can it be implemented and placed into operation. An operating urban gas network can be considered as having strong network integrity (referred to as the "normal condition"), and consequently, it can complete the "required functions", i.e., it has the capacity to supply qualified natural gas to customers in accordance with the design requirements. With increasing service time, any pipeline in the urban gas network may fail, and the failed pipeline should be isolated from the network for repair or replacement. In this case, the integrity of the urban gas network will be disrupted (referred to as the "failure condition"), and consequently, the supply capacity will be influenced to some extent. After repairing or replacing the failed pipeline, the urban gas network will resume its normal condition and regain the designed supply capacity. Therefore, the urban gas network belongs to a type of repairable system, and its supply capacity relates to its integrity.

During the service time of an urban gas network, all of the pipelines undergo mutual conversions between the normal state and the failure state. Due to corrosion, aging, third-party damage or other reasons, some pipelines in the normal state will be converted to the failure state with a certain probability; in contrast, through repair or replacement, other pipelines in the failure state will be converted to the normal state with another certain probability. These mutual conversions of all of the pipelines will lead to the diversity of the integrity state of the urban gas network.

Considering an urban gas network consisting of N pipelines, for any pipeline j (j=1, 2, ..., N), a two-valued function  $x_j(t)$  is employed to represent the state of the pipeline j at a certain time t, that

is, if the pipeline j is in normal state at the certain time t,  $x_i(t) = 1$ ;

otherwise  $x_j(t) = 0$ , representing the failure state. Consequently, all of the state functions of *N* pipelines constitute the integrity state vector of the urban gas network, as expressed by equation (1):

$$X(t) = [x_1(t), x_2(t), \cdots x_j(t), \cdots x_N(t)]$$
(1)

Here, t is the service time after the urban gas network is put into operation; X(t) is the integrity state vector of the urban gas network at time t;  $x_j(t)$  is the state function of any pipeline j ( $j=1, 2, \dots, N$ ) at time t; and N is the number of pipelines in the urban gas network.

It is assumed that only a single pipeline failure per unit time will occur, and consequently, an urban gas network with N pipelines will have (N+1) conditions, including a normal condition and N failure conditions.

The required functions of urban gas networks are to supply qualified natural gas in accordance with the design requirements of customers. The failure of any single pipeline may influence the supply capacity of an urban gas network, whereas different pipelines have different influences, due to their different positions within the network. During the service time, the integrity of an urban gas network always changes with the state changes of each pipeline, so the supply capacity of the urban gas network is a dynamic process with the change in the service time, as described by equation (2):

$$Q(t) = \phi[X(t)] \tag{2}$$

Here, Q(t) is the supply capacity of an urban gas network at service time *t*.

According to the system reliability theory, the gas supply reliability of an urban gas network at service time t can be defined as the ratio of the supply capacity at time t to the designed supply capacity of the urban gas network, as is shown in equation (3) [2, 3, 12]:

$$R_{\rm net}(t) = \frac{Q(t)}{Q_0} \tag{3}$$

Here,  $R_{net}(t)$  is the supply reliability of an urban gas network at service time t and  $Q_0$  is the designed capacity supply of the urban gas network.

As stated previously, during the service time, all of the pipelines in an urban gas network undergo mutual conversions between the normal state and the failure state. At time t, if the urban gas network has high integrity, it can complete the required functions and consequently has the designed supply capacity  $Q_0$ ; on the contrary; if any pipeline j is isolated for repair due to failure, the urban gas network will be converted into the fault condition j and will lose a certain amount of supply capacity  $\Delta Q_j$ , with the supply capacity decreased to  $Q_j$ .

As previously mentioned, an urban gas network with N pipelines has (N+1) conditions, including one normal condition and N failure conditions. It is obvious that the condition of an urban gas network at time t is associated with the structure reliability of each pipeline; nevertheless, the supply capacity in each specific condition of the urban gas network is associated with the hydraulic reliability. The change in the integrity state of an urban gas network can be regarded as a homogeneous Markov process; thus, according to formula (3), the supply reliability of the urban gas network at time t can be derived as follows [2, 11]:

$$R_{\rm net}(t) = 1 - \sum_{j=1}^{N} \frac{\Delta Q_j}{Q_0} \frac{\lambda_j l_j}{\sum (\lambda_j + \mu_j) l_j} [1 - e^{-(\sum \lambda_j + \mu_j) l_j t}]$$
(4)

Here,  $\Delta Q_j$  is the lost supply capacity of an urban gas network under failure condition *j*, compared to the capacity under the normal condition, referred as to the flow reduction, in Nm<sup>3</sup>/h;  $\lambda_j$  is the failure rate of pipeline *j*, in times/(km·a);  $l_j$  is the length of pipeline *j*, in km; and  $\mu_j$  is the repair rate of pipeline *j*, in times/(km·a).

As shown in equation (4), the supply reliability of an urban gas network changes with the service time *t*. Under a given service time, the supply reliability of an urban gas network is not only related to the flow reduction under each failure condition but is also closely related to the repair rate and failure rate of each pipeline.

Equation (4) also shows that the supply reliability of an urban gas network can achieve a comprehensive evaluation of the work capacity of the entire urban gas network, as it takes into account the combined influence of the structural reliability and hydraulic reliability. To make the evaluation of gas supply reliability more operational and practical, the following will make full use of some research achievements in the field of structural reliability and hydraulic reliability to calculate the parameters in the gas supply reliability evaluation, such as the pipeline failure rate, pipeline repair rate, and flow reduction of the urban gas network under different failure conditions.

#### 3. Calculation of the gas supply reliability parameters

#### 3.1. Pipeline failure rate

The scientific determination of the pipeline failure rate requires a complete and detailed failure statistics database. The European Gas Pipeline Incident Data Group (EGIG), with abundant gas pipeline failure data from 15 countries, including France, Germany, Denmark, etc., is useful in determining the pipeline failure rate and improving the failure level [13-15]. Unfortunately, the construction of urban gas pipeline failure databases has not attracted adequate attention and is therefore relatively less advanced in China; moreover, the abundance and validity of the collected data are also limited. At present, the determination of the urban gas pipeline failure rate in China is mainly based on expert knowledge, such as the Kent method, fault tree analysis, analytic hierarchy process (AHP), the fuzzy comprehensive evaluation method, etc. [16-18]. However, methods based on expert knowledge can only obtain the relative values of pipeline failure rate rather than absolute values, not to mention these methods are very subjective.

At present, there has been considerable research into the reliability of pipeline structures, and its main purpose has been to obtain the failure probability of pipelines [19-21]. Moreover, according to system reliability theory, the failure rate is defined as failure probability in unit time [22, 23]. That is, for a properly functioning pipeline that has not failed until time t, the failure rate is the probability of the pipeline failure occurring in the next unit time dt. The relationship between the two is as follows:

$$\lambda(t) = -\frac{1}{1 - P_{\rm f}(t)} \frac{d[1 - P_{\rm r}(t)]}{dt} = \frac{dP_{\rm f}(t) / dt}{1 - P_{\rm f}(t)}$$
(5)

Here,  $\lambda(t)$  is the pipeline failure rate, in times/(km·a);  $P_f(t)$  is the failure probability of the pipeline; and t is the service time of the operating pipeline, in a.

When there is no sufficient pipeline failure database, it is feasible to adopt the method based on structural reliability analysis to determine the pipeline failure rate [24-26]. The main calculation processes of the method are as follows:

(1) The parameters affecting the pipeline failure are regarded as random variables. According to related information for a given pipeline, the probability distribution types and statistical features such as the mean and variance of the random parameters are reasonably determined.

(2) The possible failure model for the pipeline is analyzed. According to the stress-strength interference theory, the limit state equation of pipeline failure is established.

(3) Using the Monte Carlo method, or Linear Second Order Moment Method or any other related algorithm, the pipeline structural reliability is analyzed, and consequently, the failure probability of the pipeline can be obtained.

(4) According to the relationship between failure probability and failure rate, i.e., equation (5), the pipeline failure rate can be calculated.

In the reference [27] by the authors, the failure probability of an urban gas pipeline is analyzed by using the structural reliability theory, and the changes with service time are obtained, as shown in Figure 1.



Fig. 1. Failure probability of the pipeline changes with service time [27].

Taking into account  $P_{\rm f}(t) = 1$  when t=0, the relationship between failure probability and the failure rate of the above specified pipeline can be derived from equation (5), as follows:

$$\lambda(t) = -\frac{\ln P_{\rm r}(t)}{t} = -\frac{\ln(1 - P_{\rm f}(t))}{t}$$
(6)

According to equation (6) and the change in the failure probability with service time in Figure 1, the pipeline failure rate of different service times can be determined, as shown in Figure 2.



Fig. 2. Pipeline failure rate changes with service time.

As shown in Fig. 2, the pipeline failure rate curve based on the structural reliability analysis method presents all of the features of the "bathtub curve", which is considered to be the typical failure rate curve. In the early stages of operation, the pipeline failure rate is rather high and gradually decreases with the service time. In the middle stages, the pipeline failure rate is maintained at a lower level, which can be approximated as a constant for convenience of discussion, i.e.,  $\lambda(t) = \lambda = \text{Constant}$ . Take t=20a as an example; the failure rate  $\lambda$  is

only  $0.065 \times 10^{-3}$  times/(km·a). In the late stages, however, the pipeline failure rate increases annually.

### 3.2. Pipeline repair rate

The pipeline repair rate is the probability that a failed pipe that was not repaired during time t can be repaired in the next unit time dt.

The pipeline repair rate is associated with the maintenance time of the pipeline. The maintenance time of the pipeline is defined as the time taken from failure detection to the recovery of normal function, including the time of failure diagnosis, failure location, failure post-processing, recovery, etc. This time depends on the enterprise's management level, maintenance equipment and maintenance capability, etc., so the repair rates of all pipelines of the same enterprise have the same value.

Considering that different gas supply enterprises have different operation management levels, maintenance equipment and maintenance capacities, and the above-mentioned factors also affect the pipeline failure rate of the corresponding enterprise, the pipeline repair rate of different enterprises can be determined according to the average value of all of the pipeline failure rates of the corresponding enterprise.

In general, the pipeline repair rate has an order of magnitude difference compared to the pipeline failure rate, as in the following function relation [11].

$$\mu = (10 \sim 1000)\overline{\lambda} \tag{7}$$

Here,  $\mu$  is the repair rate of all pipelines of an enterprise, in times/ (km·a);  $\overline{\lambda}$  is the average value of all pipeline failure rates of the corresponding enterprise, in times/(km·a).

## 3.3. Flow reduction of an urban gas network under different failure conditions

As is known from Equation (4), the supply reliability evaluation of an urban gas network involves flow reduction of the network under each failure condition, which implies that N flow reductions require individual calculation for an urban gas network consisting of N pipelines, which can, in theory, be performed through the network hydraulic regime analysis. However, when any single pipeline fails and needs to be isolated from an urban network for repair, the flow through some pipelines will change, as will the flow directions in some other pipelines, leading to ambiguity in the series-parallel relationships between the pipelines in the network, as well as an increase in the complexity of the network hydraulic regime analysis.

Because of the above situation, the determination of the flow reduction of an urban gas network under different failure conditions has not yet been reasonably solved. In reference [11], the flow reduction is obtained from the static load diagram of the network, which is obviously impractical. In reference [2], the hydraulic regime of an urban gas network under normal conditions is analyzed, and the flow through each pipeline under normal conditions is approximately considered to be the flow reduction under the corresponding failure condition . This simple method allows for simultaneous the determination of the flow reduction under each failure condition with the hydraulic calculation of the network such that it has certain operability. However, although the actual flow reduction due to the failure of any one pipeline is positively related to the flow through the corresponding pipeline under normal conditions, it is also affected by many other factors, such as the utilization coefficient of pressure drop, the topology structure of the urban gas network, etc. The larger the scale of the urban gas network, the greater is the inaccuracy of the simple method.

It is considered that the emphasis of hydraulic reliability analysis is to study the influence of any failure pipeline on the whole gas network by using fluid mechanics. In reference [8], the hydraulic reliability of an urban loop high-pressure gas network is analyzed, and a feasible method for determining the actual nodal flow is presented. After proper adjustments, the method can also be employed to calculate the flow reduction of an urban gas network under failure conditions. As for an urban gas network consisting of N pipelines and M consumer nodes, the steps for the flow reduction  $\sigma_{equiv}$  of the network under failure conditions.

(1) According to the known designed flow of each consumer node  $Q_i$  (*i*=1, 2, ..., M), simulate the hydraulic regime of the urban gas network under normal conditions.

(2) If any single pipeline fails and needs to be isolated from the urban gas network, it is first considered that the pressure  $P_i$  (*i*=1,2,...,M) of each node in the network can still meet the required minimum pressure  $P^{\min}$  of the network. That is, assume that the actual nodal flow  $Q_i^{avl}$  (*i*=1, 2, ...,M) of each consumer node is equal to the designed nodal flow  $Q_i$  under each failure condition *j*.

(3) According to the actual nodal flow  $Q_i^{\text{avl}}$  and the new topology of the urban gas network due to the isolation of failure pipeline *j*, simulate each nodal pressure  $P_i$  under failure condition *j*.

(4) The pressures of all of the nodes in the urban gas network are checked to determine whether the inequality  $P_i \ge P^{\min}$  is true. If "yes", the network pressure reserve is capable of compensating for extra pressure losses despite the occurrence of a failure. That is, the network has the ability to convey  $Q_i^{avl}$  for all of the consumer nodes in the network, such that  $Q_i^{avl}$  is a reasonable value.

Otherwise, the network is unable to convey qualified natural gas to satisfy  $Q_i^{\text{avl}}$  and then moves on to step (5) to adjust  $Q_i^{\text{avl}}$ .

(5) The node with the lowest pressure in the urban gas network is identified, and the  $Q_i^{\text{avl}}$  of this node is multiplied by 0.99 to gradually reduce its actual flow. Steps (3), (4), and (5) are repeated until the pressures of all of the nodes satisfy the minimum required pressure  $P^{\min}$ .

6 The final adjusted nodal flow  $Q_i$  is the actual flow of each consumer node. It is evident that the flow reduction  $\sigma_{equiv}$  of the urban gas network under failure condition j is equal to

$$(\sum_{i=1}^M Q_i - \sum_{i=1}^M Q_i^{\text{avl}}) \ .$$

According to the above steps to write the program, by adding a loop statement inside the program, the flow reductions of an urban gas network under all failure conditions can be calculated both easily and quickly.

### 4. Example

Using the above method, the gas supply reliability of an urban gas network can be expediently evaluated. The main purpose of the evaluation is for an overall consideration of the structural reliability of all of the pipeline units and the hydraulic regimes under all the failure conditions to have a comprehensive capacity analysis of an urban gas network.

Considering the complexity of an urban gas network system consisting of dozens or even hundreds of pipelines, making it difficult to identify some of the most essential conclusions, this section employs the simple double-loop gas network in reference [8] to illustrate the process and the feasibility of this evaluation method. As long as this method is feasible, it can be extended to any complex urban gas network.

An urban gas network is shown in Fig. 3. Seven branches, numbered from 1 to 7 (in parentheses), represent seven high-pressure gas pipelines, with the impedance of each being 1.2. Each pipeline is equipped with two valves, one at each end (not shown in the figure), to isolate the network system when it fails. (1) to (5) represent five consumer nodes, which can be regarded as five high-medium pressure



Fig. 3. Schematic of an urban gas network

regulating stations, supplying natural gas to residential, commercial or industrial areas as previously described. Node 6 represents the gas source station. The arrows in the figure represent the natural gas flow directions. Under normal conditions, the pressure of node 6 is held constant at 4.0 MPa, while the designed flow of each consumer node is 1000 Nm<sup>3</sup>/h. The minimum required pressure in the gas network is 2.5 MPa.

According to equation (1) and the network topological structure in Fig. 3, the integrity state vector of the urban gas network can be expressed as follows:

$$\mathbf{X}(t) = [x_1(t), x_2(t), x_3(t), x_4(t), x_5(t), x_6(t), x_7(t)]$$
(8)

Because the failure rate and failure time of each pipeline are different, the urban gas network with 7 pipelines may have 8 conditions during the service time. They can be expressed as:

$$\begin{split} \mathbf{X}_0(t) &= [1, 1, 1, 1, 1, 1, 1, 1], \\ \mathbf{X}_1(t) &= [0, 1, 1, 1, 1, 1, 1], \\ \mathbf{X}_2(t) &= [1, 0, 1, 1, 1, 1, 1], \\ \mathbf{X}_3(t) &= [1, 1, 0, 1, 1, 1, 1], \\ \mathbf{X}_4(t) &= [1, 1, 1, 0, 1, 1, 1], \\ \mathbf{X}_5(t) &= [1, 1, 1, 1, 0, 1, 1], \\ \mathbf{X}_6(t) &= [1, 1, 1, 1, 1, 0, 1], \\ \mathbf{X}_7(t) &= [1, 1, 1, 1, 1, 1, 0]. \end{split}$$

Among them,  $X_0(t)$  represents the urban gas network in normal conditions and can satisfy all of the designed supply capacity. Each of the remaining seven vectors respectively represents one failure condition of the urban gas network and can only satisfy part of the designed supply capacity.

The conversion of the urban gas network from normal conditions to each failure condition is caused by the failure of any of the 7 pipelines. Each single pipeline failure corresponds to a unique failure condition. Considering that different pipelines have different design parameters, construction technology, service times, operating environments, etc., the failure rates of each pipeline are also different. Based on investigation and statistics of the actual data of each pipeline, the failure rates of pipeline (1) to (7) can be calculated according to the method introduced in Section 3.1. Provided that the service time of the urban gas network is 10 years, the failure rate of each pipeline can be calculated, and the results are shown in Table 1.

Table 1. The failure rate of each pipeline (10-3 times/(( $km \cdot a$ ))

Pipeline number	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Failure rate	0.122	0.162	0.340	0.213	0.331	0.216	0.113

According to the method of Section 3.3, through hydraulic reliability analysis of the urban gas network, the total network flow and the flow reductions of the network under normal and seven failure conditions can be obtained. The calculation results are shown in Table 2.

Table 2. The total network flow and the flow reductions under different conditions (Nm3/h).

Condition number	Integrity state vector	Total network flow	Flow reduction
0	[1,1,1,1,1,1,1]	5000	0
1	[0,1,1,1,1,1,1]	2476	2524
2	[1,0,1,1,1,1,1]	4393	607
3	[1,1,0,1,1,1,1]	4990	10
4	[1,1,1,0,1,1,1]	4514	486
5	[1,1,1,1,0,1,1]	3746	1254
6	[1,1,1,1,1,0,1]	4905	95
7	[1,1,1,1,1,1,0]	2746	2254

Considering the enterprise's management level, maintenance equipment and maintenance capability, etc., the pipeline repair rate is assumed as 100 times that of the average value of all pipeline failure rates, i.e.,  $\mu = 100\overline{\lambda} = 100 \times \sum_{j=1}^{7} \lambda_j / 7 = 0.0214$  times/(km·a).

According to equation (4), the gas supply reliability of the urban gas network at 10 years can be calculated as follows:

$$R_{\rm net}(10) = 0.9623$$

Similarly, the changes in the gas supply reliability of the urban gas network with the service time can be calculated, as shown in Fig. 4. With increasing service life, the gas supply reliability decreases from 1.0 at the beginning to 0.914 at 50 years.

It should be noted that the improvement of gas supply reliability of urban gas networks should be considered from aspects of network planning and design, network hydraulic regime analysis, pipeline integrity management, etc. This example is used to describe the detailed process of the gas supply reliability evaluation and to illustrate the feasibility of this method. Unfortunately, until now, the use of evaluation results to guide current gas engineering design and operation management has had no standard of reference.



Fig. 4. Gas supply reliability changes with service time

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However, from the perspective of the development of technology, the gas supply reliability evaluation of urban gas networks should be applied in practical engineering, and the requirement for gas supply reliability of each specific urban network should also be introduced in the future. Certainly, the scientific requirements of gas supply reliability should be gradually accumulated through the actual operation data of many urban networks. In addition, data for different types and scales of urban gas networks should be obtained to explore different gas supply reliability ranges, as well as to make timely adjustments according to technological and economic changes.

### 5. Conclusion

An urban gas network is one of the lifeline projects of urban areas, and its supply capacity is not only related to the structural reliability of each pipeline but also to the hydraulic conditions of the whole network. Structure reliability analysis and hydraulic reliability analysis offer different perspectives of an urban gas network and reflect different aspects of the network working conditions; however, they cannot be used to make a comprehensive capacity analysis of an urban gas network.

The system reliability theory is employed in this study to examine gas supply reliability of an urban gas network. The research achievements both in the structural reliability and hydraulic reliability fields are fully utilized to calculate the parameters in the gas supply reliability evaluation, making the evaluation more operational and practical. Finally, using an example of a simple double-loop gas network, the detailed process of the gas supply reliability evaluation of an urban gas network is described, and the feasibility of this evaluation method is also illustrated.

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### References

- 1. Sukharev M G, Karasevich A M. Reliability models for gas supply systems. Automation and Remote Control 2010; 71(7): 1415–1424, https://doi.org/10.1134/S0005117910070155.
- 2. Yan M Q. Reliability assessment on gas supply of gas transmission and distribution network. Gas & Heat 2014; 34(1): 01-05.
- Su H, Zhang J J, Zio E, et al. An integrated systemic method for supply reliability assessment of natural gas pipeline networks. Applied Energy 2018; 209: 489-501, https://doi.org/10.1016/j.apenergy.2017.10.108.
- 4. Kucheryavyi V I, Milkov S N. Strength reliability of gas-supply pipes of large diameter. Journal of Machinery Manufacture and Reliability 2014; 43(5): 448-452, https://doi.org/10.3103/S1052618814050094.
- 5. Kong F T, Pesinis K. Reliability prediction for corroding natural gas pipelines. Tunnelling and Underground Space Technology 2017; 65: 91-105, https://doi.org/10.1016/j.tust.2017.02.009.
- 6. Szybka J, Boniec Z, Pilch R. Forecasting the failure of a thermal pipeline on the basis of risk assessment and exploitation analysis. Eksploatacja i Niezawodnose Maintenance and Reliability 2011; 4: 5-10.
- Tchórzewska-Cieślak B, Pietrucha-Urbanik K, Urbanik M. Analysis of the gas network failure and failure prediction using the Monte Carlo simulation method. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2016; 18(2): 254–259, https://doi.org/10.17531/ ein.2016.2.13.
- 8. Li J, Qin C K, Yan M Q, et al. Hydraulic reliability analysis of an urban loop high-pressure gas network. Journal of Natural Gas Science and Engineering 2016; 28: 372–378, https://doi.org/10.1016/j.jngse.2015.12.010.
- 9. Gheisia A, Naser G. Simultaneous multi-pipe failure impact on reliability of water distribution systems. Procedia Engineering 2014; 89: 326–332, https://doi.org/10.1016/j.proeng.2014.11.195.
- 10. Myers A. Complex system reliability. Berlin: Springer Publishers, 2010, https://doi.org/10.1007/978-1-84996-414-2.
- 11. Ionin, Li Y, Wang M. Gas Supply. Beijing: China Building Industry Press, 1986.
- 12. Marvin R, Arnljot H. System reliability theory: models, statistical methods, and applications, 2nd Edition. Wiley Online Library, 2003.
- 13. EGIG- European Gas Pipeline Incident Report Group. Report of the European Gas Pipeline Incident Group 2015.
- 14. Mather J, Blackmore C, Petrie A, et al. An assessment of measures in use for gas pipelines to mitigate against damage caused by third party activity. HSE Contract Research Report 2001.
- 15. Vianello C, Maschio G. Quantitative risk assessment of the Italian gas distribution network. Journal of Loss Prevention in The Process Industries 2014; 32(1): 5-17, https://doi.org/10.1016/j.jlp.2014.07.004.
- 16. Dong Y, Yu D. Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis. Journal of Loss Prevention in The Process Industries 2005; 18(2): 83-88, https://doi.org/10.1016/j.jlp.2004.12.003.
- 17. Guo Y B, Meng X L, Meng T, et al. A novel method of risk assessment based on cloud inference for natural gas pipelines. Journal of Natural Gas Science and Engineering 2016; 30: 421–429, https://doi.org/10.1016/j.jngse.2016.02.051.
- 18. Liang W, Hu J, Zhang L, et al. Assessing and classifying risk of pipeline third-party interference based on fault tree and SOM. Engineering Applications of Artificial Intelligence 2012; 25(3): 594-608, https://doi.org/10.1016/j.engappai.2011.08.010.
- Dundulis G, Žutautaitė I, Janulioni R, et al. Integrated failure probability estimation based on structural integrity analysis and failure data: natural gas pipeline case. Reliability Engineering & System Safety 2016; 156: 195-202, https://doi.org/10.1016/j.ress.2016.08.003.
- Qian G, Niffenegger M, Zhou W, et al.. Effect of correlated input parameters on the failure probability of pipelines with corrosion defects by using FITNET FFS procedure. International Journal of Pressure Vessels and Piping 2013; 105(4): 19–27, https://doi.org/10.1016/j. ijpvp.2013.02.004.
- 21. Zhao Y F, Song M D. Failure analysis of a natural gas pipeline. Engineering Failure Analysis 2016; 63(5): 61-71, https://doi.org/10.1016/j. engfailanal.2016.02.023.
- 22. Gertsbakh I B. Statistical reliability theory. Wiley Online Library, 1989.
- 23. Elsayed A. Reliability Engineering, 2nd Edition. Wiley Online Library, 2012.
- 24. Robert E M, Andre T B. Structural reliability analysis and prediction, 3rd Edition. New Jersey: Wiley-Blackwell, 2018.
- 25. Bisaggio H C, Netto T A. Predictive analyses of the integrity of corroded pipelines based on concepts of structural reliability and Bayesian inference. Marine Structures 2015; 41: 180-199. https://doi.org/10.1016/j.marstruc.2015.02.003
- 26. Huang X M, Li M Z, Peng S N, et al. Assessment methods of failure probability on gas pipelines. Acta Petrolei Sinica 2010; 31(4): 664-667.
- 27. Qin C K, Li J, Yan M Q, et al. Analysis of failure probability of urban underground gas pipelines under corrosion effect. Natural Gas Industry 2015; 35(5): 85–89.

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# THE DYNAMICS OF WEAR OF CUTTING INSERTS DURING TURNING OF NON-HOMOGENEOUS MATERIAL ON THE EXAMPLE OF POLYMER CONCRETE

## DYNAMIKA ZUŻYCIA PŁYTEK SKRAWAJĄCYCH PODCZAS TOCZENIA NIEJEDNORODNEGO MATERIAŁU NA PRZYKŁADZIE POLIMEROBETONU\*

The article presents the results of studies on the dynamics of wear of five different cutting inserts (for machining difficult-to-cut materials, for finishing cast iron machining, for roughing cast iron machining, for steel machining and for stainless steel machining) during turning a non-homogeneous material such as polymer concrete. Polymer concrete is a difficult-to-cut, anisotropic, composite material. During the tests, a record of the components of the cutting force in real time was made. After each machining pass, the Ra and Rz surface roughness values were measured in the direction perpendicular to the machining marks and photos were taken under the microscope of the inserts corners, on the basis of which the width of major flank wear land and the width of minor flank wear land were measured. The view of each insert after the tests was also presented. Finally, the conclusions about the dynamics of wear of inserts taking part in the study as well as their applicability during polymer concrete turning were formulated.

Keywords: dynamic of wear, turning, polymer concrete, cast iron, surface roughness, cutting force.

W niniejszym artykule zaprezentowano wyniki badań dynamiki zużycia pięciu różnych płytek skrawających (do obróbki materiałów trudnoobrabialnych, do wykończeniowej obróbki żeliwa, do zgrubnej obróbki żeliwa, do obróbki stali oraz do obróbki stali nierdzewnej) podczas toczenia niejednorodnego materiału, jakim jest polimerobeton. Polimerobeton jest trudnoobrabialnym, anizotropowym materiałem kompozytowym. Podczas wykonywania badań dokonywany był zapis składowych siły skrawania w czasie rzeczywistym. Po wykonaniu każdego przejścia obróbczego zostały zmierzone wartości parametrów chropowatości Ra oraz Rz obrobionej powierzchni w kierunku prostopadłym do śladów obróbki oraz zostały wykonane zdjęcia pod mikroskopem naroży płytek, na podstawie których zmierzono zużycie głównej powierzchni przyłożenia oraz pomocniczej powierzchni przyłożenia. Zaprezentowano również wygląd każdej z płytek po przeprowadzonych badaniach. Na koniec sformułowano wnioski na temat dynamiki zużycia płytek biorących udział w badaniu, a także stosowalności ich podczas toczenia polimerobetonu.

*Słowa kluczowe:* dynamika zużycia, toczenie, polimerobeton, odlew mineralny, chropowatość powierzchni, siły skrawania.

#### 1. Introduction

Polymer concrete (PC, mineral cast) is a multi-component composite material in which the filler is mostly inorganic aggregate grains, whereas the binder is resins [1, 2, 4, 6, 7, 13]. PC is used for the production of various products, such as prefabricated sanitary devices, corrosion resistant constructions, acid tanks, wells, drains, highways, repair materials or machine parts, such as guides, tables or machine tool beds [11]. The increasingly common use of mineral cast forces the use of more precise molds for their implementation. Depending on the requirements for precision, dimensional tolerances, surface roughness, PC's can be made in wooden, plastic, metal, cast iron or combined molds [6]. For this reason, in order to obtain the appropriate parameters of the surface layer, elements made of mineral cast, after removing from the mold, should be machined. The heterogeneity of the material which is the polymer concrete makes the wear of the cutting tool very dynamic. The structure of a composite material such as PC includes very hard aggregates and a soft bonding material (polymer resin). In addition to the differences in the hardness of the materials that make up the composite, there is a significant difference in the method of material separation during processing (cracking, chip formation, etc.) and significant differences in the thermal energy flow during the cutting process between the various materials included in the polymer concrete. Such a structure of the machined material results in very complicated conditions in which the machining tool works. Hence it is need to define and investigate the mechanism of wear of cutting tools during the processing of polymer concrete.

In the cutting process, the working surfaces of the tool stay in contact with the chip and surfaces of the workpiece moving in relation to them. Phenomena occurring on these surfaces cause wear of the cutting tool, mainly consisting in changing the geometry of the tool in

<sup>(\*)</sup> Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

its working part and consequently the loss of the cutting ability of the tool [3]. These phenomena include:

- mechanical abrasion,
- adhesion,
- diffusion,
- chemical phenomena (mainly oxidation).

The share of each phenomenon in the tool wear process is not the same and depends on the machining conditions, the greatest impact of which is the cutting speed [3]. Other forms of tool wear are:

- micro-crushing of tool material around the cutting edge,
- plastic deformation of the tool material,
- microcracks in the tool material.

The tool can also be damaged by breakage a large volume of material in the working part of the tool as a result of exceeding the immediate or fatigue strength of the material [3]. The above mentioned processes cause that the working part of the tool changes the geometry losing its cutting capacity.

In order to determine the wear dynamics of cutting tools, the indicators are used which are using a number of parameters, describing the flank wear and the face wear [3, 9, 10]. Figure 1 shows wear indicators for a turning tool [8].



Fig. 1. Indicators of turning tool wear [8]

On the flank surface, wear occurs along the cutting edge in the form of a strip of variable width. Increased corner wear  $(VB_C)$  is mainly caused by concentration of stresses and higher temperature in this cutting zone, whereas groove  $(VB_N)$  is caused by the influence of the surface layer, most often by hardening after the previous operation (e.g. a casting shell) and chemical processes (e.g. oxidation process) [8].

On the tool face surface, wear occurs in the form of a crater located, in most cases, at a distance from the cutting edge (KM – distance between the center of the crater and the cutting edge or KB – width of the crater). This is the zone in which the highest temperature on the face occurs during cutting [8].

The wear on the flank surface occurs practically under all machining conditions, while significant wear on the tool face is characteristic of high cutting speeds. As a measure of wear on the flank surface, the width of the  $VB_B$  in the central active part of the main cutting edge is assumed, whereas the wear on the tool face is usually described by the depth of the crater KT [8].

The wear of the cutting tool is accompanied by such phenomena as:

- deterioration of the smoothness of the machined surface,
- · change in the overall dimensions of the workpiece,
- increase in the level of vibrations and noise,
- increase in the cutting temperature.

Most of these phenomena are used to actively detect tool wear, e.g. in automated production.

The process of wear of the cutting tool is a process that takes place during the tool life period with different intensity. Typical wears versus time are shown in Figure 2 [8].



In most cases, three characteristic phases of abrasive wear of the tool can be distinguished [8] as follows:

I – the initial, short-term phase (section AB) is mainly caused by the surface reaching the tool and the removal of surface unevenness resulting from the sharpening,

II – the second phase (BC section) is characterized by low consumption increase and is generally 90% of the total working time of the tool,

 $\rm III-$  in the third phase (CD section) the VB increases rapidly, which is caused by the increase of forces and temperature during the machining with the worn tool. The entry of the tool into this period of wear means its bluntness.

The work of the tool in the third wear period is unprofitable because it gives small increases in cutting time at the expense of high tool wear and a significant increase in sharpening costs. In addition, there is a real threat of destruction of the tool and the workpiece in the case of catastrophic wear of the tool [8].

Such a wear mechanism of the cutting tool has been described in the literature and relates to the cutting of isotropic materials. The polymer concrete as an anisotropic material is the subject of this study. In order to determine the dynamics of wear of the cutting inserts during the turning process, the wear index of the cutting tool VB of the major flank (VBm<sub>a</sub>fwl) and the minor flank (VBm<sub>i</sub>fwl) were determined. Surface roughness tests of the machined workpiece as well as measurements of the cutting force components were also carried out.

#### 2. Nomenclature

v <sub>c</sub>	cutting speed
f	feed
a <sub>p</sub>	depth of cut
F <sub>x</sub>	resistance force
Fy	feed force
Fz	peripheral force
F	cutting force
Ra	surface roughness
Rz	height of roughness
M <sub>a</sub> F	major flank
M <sub>i</sub> F	minor flank
VB	tool wear
VBm <sub>a</sub> fwl	width of major flank wear land
VBm <sub>i</sub> fwl	width of minor flank wear land

### 3. Materials and methodology

#### 3.1. Polymer concrete

The material used for the tests was a polymer concrete offered by the RAMPF company, available on the market under the name EPU-CRET 140/5 [5]. It is a material used for casting small machine parts, i.e. guides, tables or beds, weighing less than 500 kg. It consists of aggregates with dimensions ranging from a few micrometers up to 5mm. In order to prepare the samples, the mass proportions of the hardener and epoxy resin were firstly mixed thoroughly until a homogeneous consistency was obtained. The appropriate mass fraction of the mineral filler was then added and the whole was mixed again until a uniform appearance of the composition was obtained. The mixture prepared in this way was covered with a mold, ensuring proper concentration of the batch in order to avoid air bubbles forming inside the samples. Then the sample solidified in the form for 24 h, taking at the same time 80-90% hardness, and after removing the sample from the mold, the whole was still aged for 14 days, taking full hardness. A series of cylindrical samples with dimensions: diameter Ø40 mm and height 60 mm were prepared for the tests. Figure 3 shows the view of a sample prepared for testing, placed in a three-jaw chuck of a CNC lathe.



Fig. 3. The view of sample made of polymer concrete

#### 3.2. Turning inserts

The research was carried out for 5 types of Sandvik cutting inserts:

- WNGA 060408 S01030A 7015 for machining difficult-to-cut materials,
- WNMG 060408 KF 3005 for finishing cast iron machining,
- WNMG 060408 KR 3205 for roughing cast iron machining,
- WNMG 060408 PM 4225 for steel machining,
- WNMG 060404 WF 2015 for stainless steel machining.

 Table 1. List of cutting parameters for individual inserts

Table 1 presents a summary of the cutting parameters recommended by the manufacturer for individual inserts.

The WNGA 060408 S01030A 7015 insert is designed for machining difficult-to-cut materials. Cast iron turning inserts (WNGA 060408 KF 3005 and WNMG 060408 KR 3205) have been selected for testing due to their improved machining properties. Cast iron can be treated as a non-homogeneous material. In cast iron parts, such as machine tool bodies, there are various types of pores, inclusions, etc. that make machining of such an element a complicated process. In such a cast there may also be mineral inclusions just below the surface as a result of the casting process, e.g. from sand molds. Inserts WNMG 060408 PM 4225 and WNMG 060404 WF 2015 were selected for testing in order to compare the quality of machined polymer concrete using inserts intended for processing of traditional construction materials such as steels.

#### 3.3. Methodology

The research was carried out on the HAAS lathe with the catalog number SL10 in the Institute of Machine Tools and Production Engineering at the Lodz University of Technology. Longitudinal turning processes were carried out with the following parameters, which were determined during preliminary tests:

- cutting speed  $v_c = 50$  m/min,
- feed f = 0.2 mm/rev,
- depth of cut  $a_p = 0.25$  mm.

During the cutting process, a cooling lubricant was fed into the cutting zone. Due to lubricating properties, the fluid caused a drop in processing temperature and lower dust content.

During the tests, a cutting force components were recorded to determine the total cutting force. The measurement path consisted of Kistler 9121 dynamometer, Kistler 5070A amplifier and recorder in the form of an AC transducer card for the 2855A4 type PCI bus mounted in a PC computer. After each machining pass, the roughness values Ra and Rz of the machined surface were measured in the direction perpendicular to the machining marks (according to the PN-EN ISO 4287:1999 [12]). A portable Mitutoyo SJ-210 roughness gauge was used for this purpose. Photographs were also taken under the microscope of the inserts corners (noses), on the basis of which the width of major flank wear land and the width of minor flank wear land were measured after each machining pass. In addition, the views of each insert after the tests was presented. Each experiment was carried out 3 times. Average values and their standard deviations presented in the graphs represent the obtained results of studies on the dynamics of wear of cutting inserts during turning of non-homogeneous material on the example of polymer concrete.

#### 4. Results and discussion

During machining a mineral cast, there is mainly wear on the minor flank. However both width of the major flank wear land  $VBm_afwl$  (Fig. 4) and the width of minor flank wear land  $VBm_ifwl$  (Fig. 5) were taken into account for the wear value assessment. After each pass, the

Parameter	WNGA 060408 S01030A 7015	WNMG 060408 KF 3005	WNMG 060408 KR 3205	WNMG 060408 PM 4225	WNMG 060404 WF 2015
Depth of cut a <sub>p</sub> [mm]	0.07 ÷ 0.80	0.20 ÷ 2.00	0.24 ÷ 4.50	0.50 ÷ 4.00	0.30 ÷ 2.00
Feed f [mm/rev]	0.05 ÷ 0.30	0.08 ÷ 0.25	0.17 ÷ 0.42	0.15 ÷ 0.50	0.05 ÷ 0.25
Cutting speed v <sub>c</sub> [m/min]	150 ÷ 250	255 ÷ 280	305 ÷ 390	275 ÷ 425	260 ÷ 305

wear of the individual insert was measured. The results of these measurements are shown in the following figures, thanks to which it was possible to analyze the tool wear as a function of time.



Fig. 4. The width of major flank wear land versus time



Fig. 5. The width of minor flank wear land versus time

The highest wear was observed for WNMG 060408 PM 4225 (intended for steel machining) and WNMG 060404 WF 2015 (intended for stainless steel machining). The major flank and minor flank worn out very quickly and after 280 seconds the operation of these tools was loud. Additionally, after this time, the corner (nose) recession was found, which resulted in a decrease in the actual depth of cut, which was only 50% of the set depth of cut. The maximum recommended criterion for tool wear should not exceed VB = 0.3 mm. It was considered that with this value of the wear parameter VB the experiment should be stopped. It can be observed that the coating of the tools was not durable and resistant to abrasion. The smallest width of the major flank wear land and the minor flank wear land were achieved during turning with the tool marked WNGA 060408 S01030A 7015. Small differences in wear VB were obtained with each pass (compared to other inserts). Unfortunately, the stresses on the tool face which were obtained during machining had the effect of destroying the tool (breakage off the corner), which eliminated the plate from further tests (Figure 9a).

During each machining test, the components of the cutting force  $F_x$ ,  $F_y$  and  $F_z$  were measured in real time. On this basis, the value of the total cutting force was calculated and shown in Figure 6 as a plot of the average value of the cutting force obtained during the three-fold repetition of the experiment with the standard deviation as a function of time.

The values of the cutting force components significantly affect the accuracy and surface quality of the machined parts. The high turning forces of the mineral cast cause faster wear of the tools and the machine tool also. The lowest values of cutting force were obtained during cutting with the insert with the designation WNGA 060408



S01030A 7015. Unfortunately, during one of the experiments between 280 and 315s the insert was destroyed. For inserts marked as WNMG 060404 WF 2015 and WNMG 060408 PM 4225, after 300 seconds of machining the mineral cast, the forces were so high that during process the machine tool was excited to vibrations. On the basis of the forces courses, it can be seen the rate of wear of the tools. Due to the low wear of the WNGA 060408 S01030A 7015 insert, it retained good cutting properties for a long time, which resulted in much lower forces than in the case of other tools.

There are many factors affecting the roughness of the treated surface. Type of using tool, its geometry, machining parameters and type of workpiece. In this case the non-homogeneity of the material, which consists of aggregates grains of various sizes, makes obtaining a repeatable measurement of the machined surface complicated. It is illustrated by the large spread of the average value, presented by means



Fig. 7. The surface roughness Ra versus time





Fig. 9. Views of inserts after the machining a) WNGA 060408 S01030A 7015, b) WNMG 060408 KF 3005, c) WNMG 060408 KR 3205 d) WNMG 060408 PM 4225, e) WNMG 060404 WF 2015

of the standard deviation. The values of roughness parameters Ra and Rz are shown in Figures 7 and 8.

As predicted, the best quality of the machined surface was obtained using the WNGA 060408 S01030A 7015 insert. For this tool, the smallest values of the Ra and Rz roughness parameters were obtained, which were repeatable for each experiment. with the smallest value of standard deviation. It is worth noting that in this case, despite the tool wear, the roughness value Ra slightly increased by about 1.5  $\mu$ m, and roughness Rz by about 10  $\mu$ m compared to the initial values. For other inserts, along with the increase in tool wear, the surface roughness value increased about three times for the Ra parameter and approximately twice for Rz. This indicates a very fast abrasion of the major flank and minor flank surfaces. Therefore during measuring the roughness of the machined surface, a much larger spread of the measured values was obtained.

In addition, photos were taken under a microscope of each insert after the tests, which are presented in Figure 9.

On the basis of the conducted research, it is possible to describe the mechanism of tool wear in the case of machining of non-homogeneous materials such as polymer concrete in the scope of cutting conditions adopted during tests. Comparing graphs of the tool wear course as a function of time for isotropic materials (Fig. 2) and anisotropic materials (Fig. 4 and 5), it can be noticed that in the case of polymer concrete machining there is no clear division into 3 characteristic phases of abrasive tool wear. It can be presumed that phase I (tool run-in) proceeds from the beginning of the machining process and ends before the first measuring point (in the 35 second of the test), however, to confirm this fact, additional tests should be performed in this time interval. However, with time, the clear boundary between phase II and III is blurring, and the obtained graphs are characterized by relatively linear course. It can be interpreted as an uniform increase in tool wear during machining. Uneven, random distribution of different grain sizes (from micrometers to millimeters) in a mineral cast means that the machining of non-homogeneous material is a complex process and the conditions of this treatment are variable at any time during that process. Analyzes concerning the nature of the wear mechanism course are very difficult, and the conclusions in this respect depend on the type of material which was machined, type of cutting insert and cutting parameters. Generalizations in this field could be developed on the basis of a stochastic approach, but it would require much larger number of tests and measurements to be carried out. The research presented above outline the mechanism of wear of the cutting tool and the trends of changes in the cutting result parameters (roughness of the machined surface) of the anisotropic material which is the mineral casting.

#### 5. Summary

Based on the results of the tests, it can be clearly stated that tools for steel (WNMG 060408 PM 4225) and stainless steel (WNMG 060404 WF 2015) machining should not be used for turning a polymer concrete. During the use of these inserts, a significant increase in cutting forces, an increase in the Ra and Rz roughness parameters as well as accelerated tool wear were observed.

In addition, the tests showed that the best results for the tool with the WNGA 060408 S01030A 7015 cutting insert were obtained. In this case, the smallest roughness values Ra, ranging from 4 to 5  $\mu$ m, were obtained. When cutting with the other tools, the roughness values of the Ra parameter were obtained in the range from 4 to 8  $\mu$ m. Analyzing also the values of the width of major flank wear land and width of minor flank wear land, the WNGA 060408 S01030A 7015 insert was characterized by the smallest wear values of these surfaces, which did not exceed VB = 0.3 mm. However, in the case of other inserts, these values exceeded the accepted limit of wear even several times.

The value of cutting forces is an important indicator of the dynamics of the turning process. In this case, the cutting force was initially the lowest for the WNGA 060408 S01030A 7015 insert. However, in the second part of the tests, the lowest cutting forces were obtained for WNMG 060408 KF 3005 and WNMG 060408 KR 3205 inserts, designed for cast iron machining.

A comparison of the mechanism of wear in the cutting zone for machining isotropic materials and polymer concrete was made. Differences in the wear process that have been tested have their origin in the specificity of the composite material and in the properties of the individual components of this composite material. Due to the fact that the machining of mineral cast material is becoming more and more common, the conducted research may become the basis for the process of selecting the right cutting inserts due to their durability during turning non-homogeneous materials.

The experimental tests have shown that in the case of turning a mineral cast, the durability of the tool is a critical parameter. This applies mainly to numerically controlled machine tools. Using inserts too long without replacement can cause large unwilling errors in the shape and dimensions of the workpiece. In contrast, frequent replacement of inserts causes time-consuming and costly machine tool downtimes.

### References

- Bruni C, Forcellese A, Gabrielli F, Simoncini M. Effect of lubrication-cooling technique, insert technology and machine bed material on the workpart surface finish and tool wear in finish turning of AISI 420B. International Journal of Machine Tools & Manufacture 2006; 46: 1547-1554, https://doi.org/10.1016/j.ijmachtools.2005.09.007.
- Bruni C, Forcellese A, Gabrielli F, Simoncini M. Hard turning of an alloy steel on a machine tool with a polymer concrete bed. Journal of Materials Processing Technology 2008; 202: 493-499, https://doi.org/10.1016/j.jmatprotec.2007.10.031.
- 3. Cichosz P. Narzędzia skrawające. Warszawa: Wydawnictwa Naukowo-Techniczne, 2007.
- 4. Cortés F, Castillo G. Comparison between the dynamical properties of polymer concrete and grey cast iron for machine tool applications. Materials and Design 2007; 28: 1461-1466, https://doi.org/10.1016/j.matdes.2006.03.012.
- 5. Dane techniczne materiału odlewu mineralnego EPUMENT 140-5 GB (http://website.epucret.de/uploads/media/EPUMENT\_140-5\_GB.pdf)
- 6. Erbe T, Król J, Theska R. Mineral casting as material for machine base-frames of precision machines. Twenty-third Annual Meeting of the American Society for Precision Engineering and Twelfth ICPE, October 2008, Portland, Oregon.
- Haddad H, Al Kobaisi M. Optimization of the polymer concrete used for manufacturing bases for precision tool machines. Composites: Part B 2012; 43: 3061-3068, https://doi.org/10.1016/j.compositesb.2012.05.003.
- Instrukcja laboratoryjna do ćwiczenia OU-5 "Zużycie narzędzi skrawających" Instytut Obrabiarek i Technologii Budowy Maszyn, Wydział Mechaniczny Politechniki Łódzkiej (http://ioitbm.p.lodz.pl/labs/tw/OU-5.pdf).
- Jaworski J, Kluz R, Trzepieciński T. Operational tests of wear dynamics of drills made of low-alloy high-speed HS2-5-1 steel. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2016; 18 (2): 271-277, https://doi.org/10.17531/ein.2016.2.15.
- 10. Kuczmaszewski J, Pieśko P. Wear of milling cutters resulting from high silicon aluminium alloy cast AlSi21CuNi machining. Eksploatacja i Niezawodnosc Maintenance and Reliability 2014; 16 (1): 37-41.
- 11. Niaki M R, Fereidon A, Ahangari M G. Mechanical properties of epoxy/basalt polimer concrete: Experimental and analytical study. Structural Concrete 2017: 1-8.
- 12. Polska norma PN-EN ISO 4287:1999 Struktura geometryczna powierzchni: metoda profilowa.
- 13. Vrtanoski G, Dukovski V. Design of polimer concrete main spindle housing for CNC lathe. 13th International Scientific Conference on Achievements in Mechanical and Materials Engineering 2005.

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### Katarzyna ANTOSZ

# MAINTENANCE – IDENTIFICATION AND ANALYSIS OF THE COMPETENCY GAP

## UTRZYMANIE RUCHU – IDENTYFIKACJA I ANALIZA LUKI KOMPETENCYJNEJ\*

The efficiency of maintenance processes in an enterprise largely depends on ensuring adequate resources for its implementation. The main factor that affects the quality of these processes is competent employees. Their knowledge, skills and ability to respond to unexpected situations largely determine the efficiency of the functioning of the technical infrastructure in an enterprise. In the light of the prospects for the development of the Industry 4.0 concept, and, thus, for the development of highly automated systems, the demand for qualified maintenance employees will increase. Therefore, in order to ensure the right level of competency of maintenance workers, through the proper assessment and identification of their competency gap, is an important task of managers. In many enterprises this is not implemented. The aim of the presented work was to developed a comprehensive model of the competency assessment of maintenance workers. The implementation of the developed model enables the identification of the current level of employees' competencies and identification of the competency gap, as well as it allows to assess the effects of a failure to meet the required level of competency assessment of maintenance services employees are presented in this article. The study was carried out in manufacturing enterprises in different industries on a specific area. The results were analysed and presented in a graphic form.

Keywords: maintenance management, exploitation efficiency, workers competency, competency gap.

Efektywność działań utrzymania ruchu w przedsiębiorstwie w dużej mierze zależy od zapewnienia odpowiednich zasobów do jego realizacji. Podstawowym czynnikiem, który ma wpływ na jakość realizacji tych działań są kompetentni pracownicy. Ich wiedza, umiejętności i zdolności reagowania na nieprzewidziane sytuacje, w dużej mierze decydują o sprawności funkcjonowania posiadanej infrastruktury technicznej w przedsiębiorstwie. W świetle perspektyw rozwoju koncepcji Przemysł 4.0, a tym samym rozwoju wysoce zautomatyzowanych systemów, wzrośnie zapotrzebowanie na wykwalifikowanych pracowników utrzymania ru-chu. Dlatego ważnym zadaniem menedżerów przedsiębiorstw jest zapewnienie właściwego poziomu kompetencji pracowników utrzymania ruchu. Zastosowanie opracowanego modelu umożliwi identyfikację aktualnego poziomu kompetencji pracowników, identyfikację luki kompetencyjnej, jak również pozwoli ocenić skutki niezapewnienia wymaganego poziomu kompetencji. Dodatkowo w pracy przedstawiono wyniki badań, których celem było zidentyfikowanie rzeczywistych działań realizowanych w przedsiębiorstwach w zakresie oceny kompetencji pracowników służb utrzymania ruchu. Badania przeprowadzono w przedsiębiorstwach produkcyj-nych, w różnych branżach przemysłu na określonym obszarze. Wyniki badań opracowano i przedstawiono w postaci graficznej.

Słowa kluczowe: utrzymanie ruchu, efektywność eksploatacji, kompetencje pracowników, luka kompetencyjna.

### 1. Introduction

The present activities of designing and installing of production systems are directed towards the increase of their efficiency, flexibility and changeability. It is particularly visible in the time of the Industry 4.0 concept development, which requires from enterprises to implement IT technologies in production areas. It forces the use of more and more sophisticated and complex solutions including technological or organizational solutions connected to the data collection and analysis, technology development, the ability to react fast to both internal and external changes and improvement of current activities [9, 14, 18, 33].

Technologies production systems development is related to the necessity of introducing changes in the work organization and environment [11]. This issue is particularly essential from the point of view of ensuring the right level of maintenance activities. The result of their wrong realization are sudden interruptions in the process of production or services realization what often put enterprises at risk of tremendous financial loss [27, 28].

In the literature, some works which assess perspectives of maintenance services functioning in the context of fast industrial development can be found. Many works underline the need of ensuring the right level and the development of workers' competencies in machine maintenance. In the work [25] a wide analysis of the perspectives of the maintenance development was performed. The analysis was divided into three main areas: the basis of maintenance, technological challenges for the future and maintenance in the 4.0 Industry concept. The analysis allowed to identify certain challenges such as planning maintenance on the system level, interoperability, IT safety and longterm data management in the whole period of exploitation. Summing up, the author stressed that a new technology may influence the decrease of human errors, although the cooperation between "a human being and a machine" in exploitation activities is important. Additionally, in the works [12, 21], it was assumed that maintenance workers will need in the nearest future new skills, which will allow for effective use of new technologies and proper realization of an exploitation process with highly automated and complex systems. It will require adequate education and trainings on many levels.

<sup>(\*)</sup> Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

In the work [3] scenarios of the functioning of the future maintenance in the production realization in the times of 4.0 concept were developed. The study of scenario planning was based on the Delphi method, examining 34 forecasts concerning potential changes in the internal and external environment of the maintenance organization. Among the analysed forecasts, the need of developing maintenance workers' competencies was also found. The author underlines that in order to keep up with the technological development, crucial competencies of the workers in maintenance should be ensured. The author described high probability of the necessity of the management of the future competencies, new requirements concerning competencies, education and trainings related to the possibility of changing a competencies profile. He stresses that the management should be aware of the fact that not providing the right level of competencies is related to an ineffective maintenance process, what in turn increases susceptibility to interruptions, decreases reactions to failures and, at the same time, decreases the competitiveness of an enterprise.

Thus, there is a need of workers' educating and training as well as of the development of a new innovative method of competencies management such as e.g. competencies models, assessment and monitoring skills, using the best experience-based practices and IT tools.

# 2. The role and assessment of competencies of the workers

A competency is a combination of three elements: knowledge, skills and attitude. They distinguish a particular person who in an efficient, effective and answering the quality expectations way realizes the tasks assigned him/her. For the assessment of the used competencies there are many models which can be classified into the following five categories [13]: quantity measures (such as tests, questionnaires, interviews or regular observations), descriptions, comparative analyses, simulation methods and research method related directly to his/ her person and work environment. Competency models are developed in order to assess the level and range of the acquired competencies and they provide the possibility of identifying the areas in which these competencies should be complemented [21]. As underlined in the works [6,7], the assessment of competencies is a process of obtaining proofs and the level of competencies among people dealing with the tasks based on certain standards. The adequate competency model, for the certain area, is the one which allows to determine the levels of all the needed competencies and, additionally, indicate expressly the areas for improvement. Such a model should be exact, reliable, should not assess the level of competencies, skills and the worker's efficiency. It is especially important for the assessment of technical competencies, e.g. in the area of machines maintenance, among which one should assess professional knowledge, knowledge about activities, skills as well as the ability to make decisions on one's own [22].

The process of the development and assessment of competency is time consuming and expensive. What's more, appointing workers to a dedicated training is not always possible. This problem is particularly essential for small and medium enterprises. That's why it is important to know which competencies are available or must be developed [1].

In the literature the problem of competency assessment in different areas is described widely, e.g. in production areas [2, 10, 19, 32]. Only a few examples of the works concerning this topic can be found within competency in maintenance.

In the work [29] the authors perform the review of the assessment of skills in maintenance. The authors, through this assessment, describe strengths and weaknesses of a given worker or a given group of workers. For this assessment they propose the use of survey questions. The analysis of the assessment results obtained in this way allows to identify the gap, describe the skills needed for the effective work performance and determine a trainings schedule. The works [5, 17] present the use of a competency matrix for the assessment of a level of maintenance workers, as well as the activities realized in the autonomous machine maintenance in the Total Productive Maintenance (TPM) for operators.

In the literature, the issues on the assessment and skills enhancement of the technical service workers as well as the realization of planes maintenance operations are mentioned. In the work [4] a method of e-learning trainings in increasing the qualifications of technical service workers was proposed. Furthermore, in the work [30] the problem of the selection of workers with adequate qualifications for the realization of particular tasks related to the process of plane repairing was presented.

However, the analysed works lack a complex model of the workers' assessment in the maintenance area, a model which would allow to assess the competencies on many levels of maturity and detail. Additionally, the perspectives of the development of the maintenance area point to the need of focusing on this issue.

In connection with the above, the problem of ensuring the right level and competency in a competency assessment in a maintenance process was undertaken.

#### 3. The range and methodology of the study

This work was realized in two stages. In the first stage, the study concerning the identification of the activities realized by enterprises in the assessment of the maintenance (M) workers' competencies in the chosen enterprises from the podkarpackie voivodship was conducted. This stage was realized in the following steps:

- 1. Determining the range and area of the study.
- 2. Developing a study sheet.
- 3. Choosing enterprises for the study.
- 4. Conducting the study and analysing the results.

In the second stage, a methodology of maintenance workers' competencies assessment was proposed, and a detailed analysis as well as the possibilities of improving the assessment of workers' competencies from the randomly chosen enterprise with the use of the proposed model was conducted. This stage was realized as follows: developing a three-stage methodology of M workers' competencies assessment, choosing an enterprise, conducting the study, analysing of the obtained results, proposing changes. The detailed analysis of the obtained results was presented in the further part of this work.

#### 4. Study results

#### 4.1. The first stage of the study

#### 4.1.1. The area and realization of the study

In the first stage the study was conducted. It concerned the identification of real activities realized by the analysed enterprises in the assessment of the maintenance (M) workers' service competencies (MS). The following issues were analysed: Do the companies identify the needed competencies of M workers? Do they assess their fulfilment by the workers? Do they take any action in order to broaden or complement them? The study concerned production companies and was conducted on the specified geographical area (podkarpackie voivodship) (Poland). Within the realized study, the analysis covered the areas which directly result from the correctly performed process of the competencies assessment. This process, according to the approach presented in the work [26], should be based on the following steps:

- 1. Identification of the requirements for maintenance service workers.
- 2. Determining the demanded level of qualifications.

- 3. Conducting the competency assessment according to the specified requirements with the help of a specific method (e.g. an interview, observations).
- 4. Analysing the obtained results and undertaking further action.

The study covered the following issues:

- determining the competency requirements for particular maintenance positions/ jobs,
- analysing workers' competencies the frequency and methods,
- completing/ broadening workers' competencies with basic or professional trainings,
- developing and functioning of the work instruction on maintenance positions/jobs.

50 enterprises were invited to take part in the study. The object of the study could include a production enterprise which possessed on its grounds functioning maintenance services regardless of their organisation, and the one implementing the Lean Manufacturing philosophy assumptions. The study was conducted in the form of interviews. The representatives of the medium and top level management and the workers directly responsible for the process of supervising machines and technological devices in the company, as well as the chosen maintenance workers took part in the study. The study took the form of conjunctive closed questions. For each question the level of fulfilment in the scale 0-10 was determined. Additionally, each respondent could add his/her own remarks and observations within the marking range.

#### 4.1.2. The structure of the studied enterprises

The enterprises which took part in the study were classified according to the following criteria: industry, production type, capital type and its situation. Table 1 shows the structure of the studied enterprises.

45% (the most) enterprises are of an aviation industry, then 20% are automotive. The remaining industries include among other metal processing (10%), chemical, wood and paper (5%) and other (printing and electronics – 15%). Among the analysed enterprises medium and large batch production dominated (32%).

63% of them possessed major foreign capital, 26% were Polish capital companies and only 11% of them possessed major national capital. Most of the studied companies, that is 63%, describe their situation as developmental, 28% as stable and 11% as difficult.

#### 4.1.3. Results of the study

According to the correctly realized process of the workers' competency assessment, the first step is to identify all requirements. These

Table 1. The studied enterprises structure

requirements are directly connected to the kind and range of the works realized by the workers in particular maintenance departments. However, it also results from the way maintenance departments are organized in an enterprise. The study examined what percent of the analysed enterprises identifies maintenance workers' competencies (Fig.1).



Fig. 1. Identification of competencies in maintenance management in different size companies

The study shows that 55% of the analysed companies determine maintenance workers' competencies. The most, that is 83% of the medium enterprises identify competencies, the least, because only 27%, small enterprises. Competencies for all the workers are identified by 50% of medium, 30% of large and only 20% of small enterprises (Fig. 2). The identification of competencies for the chosen workers is realized by small and medium enterprises, 40% each. For the most of workers, competencies are identified mainly by medium, then large and small enterprises, respectively 50%, 40% and 30%.



Fig. 2. The range of the competency assessment

The next, very important step, of the competency assessment process is the level of fulfilling the identified requirements by the maintenance workers. A periodical assessment of the workers among the analysed enterprises is realized by as much as 84% of them. The most is realized by all of the analysed medium enterprises, 90% of large and only 30% of small. The most commonly used for the competency analysis is a competency matrix (large and small enterprises) as

> well as a worker's assessment sheet together with the determined assessment criteria. Such an analysis is performed annually or every two years. About 75% of the companies, after the assessment, undertake activities aiming at broadening and supplementing competencies in the form of additional trainings. They are both internal trainings conducted by the company experts, and external trainings conducted by training companies. A detailed analysis of the results obtained is presented in Fig. 3.

Criterion	Studied enterprises structure									
Size	Small a	and micro	Medium		Large					
Sile	1	.6%	21%		63%					
Industry	Aviation	Automotive	Metal processing	Wood and paper		Chemical	Other			
-	45%	20%	10% 5%		6	5%	15%			
Production type	Piece	Small batch	Medium batch	Large batch		Mass				
i i ouuouon oppo	18%	9%	32%	32	%	9%				
Capital turna	Total po	lish capital	Major polish ca	Major foreign capital						
Capital type	2	26%	11%		63%					
Company's situation	Dif	fficult	Stable	Developmental						
company s situation	1	1%	28%		61%					



Fig. 3. Improving worker's competencies

The results, presented in Fig. 3, show that only 25% of the analysed medium companies improve competencies of all their workers. However, it is worth noting that although so few companies assess their workers' competencies, many of them undertake activities in order to improve them. The worst situation is in small enterprises.

#### 4.1.4. Discussion and the analysis of data after the first step

The study shows that 45% of the enterprises do not assess the competency of their workers who realize a maintenance process. The lack of a competency assessment handicaps significantly the analysis and the possibilities of discovering the so called staff shortages i.e. competency gaps. The lack of the workers with adequate competencies may influence on machine efficiency, which is dependent on, among others, the quality of the realized preventive and corrective activities. The study also shows that almost a half of the studied companies does not identify the maintenance workers' competencies. The study results demonstrate that it is worth examining this issue as well as making enterprises aware of the importance of the machine efficiency for the production realization. This efficiency is also the result of smoothly functioning and competent maintenance services. The study points that worst situation is in small enterprises. Because it is worth showing, especially to small enterprises, how to assess the competencies, the methodology of workers' competency assessment will be developed in the further part of this article.

#### 5. The second stage of the study

#### 5.1. Methodology of the workers' assessment in maintenance

The second stage of the study considered the development of the methodology of the maintenance workers' competency assessment (Fig. 4) and its verification in an enterprise. The developed methodology consists of three levels:

- I Development of a competency matrix.
- II Indicative assessment of the level of competency on the basis of competency matrix developed.
- III Assessment of the risk of providing the level of competency.

On every level the methodology uses a different, sophistication diversified method of a competency assessment of the maintenance workers, starting from the simplest method – a competency matrix, through an indicative assessment method to the fuzzy logic. This solution will allow to combine comprehensively the methods already used in this area [17] as well as in the competency assessment of production workers [2], extending of intelligent methods, what makes a new consistent solution. The developed model enables the identification of the current level of workers' competency and competency gap as well as it allows to assess the effects of the failure to provide the required level of competency. While developing the methodology, the requirements of the competency assessment models presented in chapter 2 were taken into consideration.



Fig. 4. Methodology of the assessment of maintenance workers' competency

The proposed methodology was used for the analysis and possibilities of improving the maintenance workers' competency assessment in a chosen enterprise.

#### 5.2. Machine supervision activities in the analysed enterprise – a problem description

The first stage of the study proved that the process of maintenance service workers' competency assessment was the worst in small enterprises. That's why, a company of such a size was chosen for the further analysis. The studied production enterprise operates in a metal processing industry on the podkarpackie voivodship. The data collected by the author and the data from the work [20] were used for the analysis. The analysed company produces machine parts, as well as preparing steel structures. Additionally, it distributes steel products and industrial gases. Innovative products, timely execution of orders, highly qualified staff, efficient technical service and high quality as well as an individual approach towards the clients' needs have caused the company to be valued and trusted by its recipient.

In the analysed enterprise, several machines are supervised. They are both traditional as well as CNC machines. In most of the small enterprises, because of the small number of machines, maintenance service workers function as one-person position. In relation to this fact, machine operators are responsible for many activities connected to the current realization of autonomous activities on machines as well as maintenance activities. The situation is similar in the analysed enterprise. The main supervision over machines is done by a maintenance specialist, whereas current maintenance activities are realized by operators.

The supervision over a machine park is conducted through inspections done in the guarantee period, the assessment of a machine condition before starting the work by an operator and through the continuous monitoring of its technical condition. Realization of activities within the machine supervision is carried out independently and partly due to external companies. Within the machines supervision the information related to their load and waiting time for service is collected. An operator and quality control worker are responsible for collecting these data. Downtimes connected to planned inspections are registered in an enterprise, whereas the information on machines failures in not registered. The activities undertaken in order to prevent unplanned downtimes include: autonomous and preventive service realization, machines modernization and ordering a part of maintenance and corrective activities to external companies.

The challenge for a chosen company is determining and the analysis of competency needs not only within the current maintenance of the possessed machines types, but also within the preventive maintenance. It is also essential because, the possessed machines play a minor or major role in a production process. Improper realization of a maintenance and preventive process on the positions, particularly those machines which are bottlenecks, causes unexpected failures, and, as a result, delays in orders realization as well as financial and image consequences for the company.

In this context, it is important for the workers who operate machines and realize basic preventive actions to possess the right qualifications. In connection to this, it is necessary to assess the competencies of maintenance workers. What's more, it is vital to possess formal attitudes in order to conduct a competency analysis in machine maintenance and the possibilities of determining a competency gap to minimize *ad hoc* assessments. The lack of formalization of such a process causes, that decisions may be wrong because they are not only undertaken on the basis of the existent data and information, knowledge or experience but also on the basis of intuition or intentions of the person doing the assessment.

#### 5.3. Verification of the methodology of the workers' competency assessment in a chosen enterprise

#### 5.3.1. Level 1: Development of a competency matrix

A competency matrix systematizes the level of knowledge and skills which are possessed by a worker in the specified area. It is successfully used to manage the process of production positions standardization as well as for the activities realized in the autonomous machine maintenance in TPM for operators [2, 5, 17]. For designing a competency matrix the following steps should be performed:

#### 1. Identification of requirements in maintenance.

This step consists of the identification of the required competencies for the identified areas. A competency matrix is commonly designed for the realized activities. However, based on the author's experience concerning enterprises, it often occurs that maintenance workers are not only dedicated to the specific activities in machine supervision but also to the specific types of machines. That's why, in the presented model, it is proposed to determine workers' competencies in two areas: for the specific types of the supervised machines and for the identified activities.

#### 2. Identification of competencies for particular workers.

This step requires the assessment of the fulfilment of the required competencies for every worker. Determining the competencies should be realized for particular workers according to the established requirements and areas (machine types and activities) identified in step 1.

#### 3. Assigning competency levels.

Levels of competency determine the level of knowledge and skills in the analysed area. The proposed levels of competency developed on the basis of the works [17, 20] are presented in table 2. These levels may be presented graphically in the form of defined symbols or in numbers. For every worker, a competency level should be determined according to the identified competencies in step 2.

#### 4. Analysis of the results and determining training needs.

On the basis of the results, a competency matrix should be developed in a graphic form. The developed competency matrix will allow to identify the areas of a low competency level (a competency gap). Each identified area should be assessed. Trainings are primarily required in the area in which the most competency levels with 0 or 1 values were identified.

#### 5.3.2. Development a competency matrix in the analysed enterprise

In the analysed enterprise, a starting point for designing a matrix was to establish the most essential skills, knowledge, workers' attitudes in both the areas of the machines operated and activities realized in autonomous and preventive maintenance. The required competencies were identified in two areas: operated machines and the realized maintenance activities. In the area of the operated machines, four basic types of machines were identified. Among the realized activities, six basic activities were specified: replacement and replenishment media, machine inspection, reaction to basic failures, machine maintenance, fulfilling of the repair and defects cards and vibration measurement. The kind of identified activities results from the specificity of the works realized in the enterprise. Next, competencies for particular workers were identified and their levels were established according to table 2. On the basis of the collected information, a competency matrix was designed – table 3.

In order to assess a competency level of the assessed workers, a number of workers who possess a certain competency level on a given area should be determined quantitatively. Table 4 presents such an analysis for the given enterprise.

The area which primarily needs training is the one with the largest number of competency levels of: first with 0 value, then with 1 value. In the analysed enterprise, these activities are: vibrations measurement, replacement and replenishment media, reactions to basic failures, fulfilling repairs and defects cards, and machine operations of type 1 and 4. A training schedule should be developed for these areas.

Table 2. Levels of workers' competencies.

Level	Symbol	Characteristic
Level 4	• 4	A worker may train others.
Level 3	<b>9</b> 3	A worker may independently perform certain tasks.
Level 2	<b>2</b>	A worker possesses knowledge and improves his/his skills, but still needs supervision .
Level 1	• 1	A worker is acquiring knowledge and skills.
Level 0	⊕ 0	A worker doesn't possess knowledge or skills to perform certain tasks.

Table 3. A	competency	matrix	of workers
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		Mac	hines				Activ	vities		_
Competency levels	Machine operation type 1	Machine operation type 2	Machine operation type 3	Machine operation type 4	Replacement and replenishment media	Machine inspection	Reaction to basic failures	Machine maintenance	Fullfilling the repairs and defects cards	Vibration measurement
Worker 1	<b>1</b> 2	<b>J</b> 3	<b>J</b> 3 <b>J</b>	3	<b>J</b> 3	3	• 4	• 1	• 4	• 4
Worker 2	• 4	• 1		0	0 2	3	0 0	0 2	<b>J</b> 3	• 4
Worker 3	• 1	• 4		0	<b>J</b> 3	• 4	$\bigcirc 0$	2	<b>1</b> 2	$\bigcirc 0$
Worker 4	0 0	<b>①</b> 2	• 4 •	2	• 4	<b>3</b>	<b>3</b>	<b>3</b>	• 1	$\bigcirc 0$
Worker 5	0 0	<b>①</b> 2	00	3	0	3	• 1	3	0 0	0 0
Worker 6	<b>3</b>	• 1	• 4 •	4	0	0	<b>3</b>	• 4	0 0	• 4

Table 4. Results of a competency assessment

		Mach	nines		Activities					
Competency levels	Machine operation type 1	Machine operation type 2	Machine operation type 3	Machine operation type 4	Replacement and replenishmer media	Machine inspection	Reaction to basic failures	Machine maintenance	Fullfilling the repairs and defects cards	Vibration measurement
•4	1	1	2	1	1	1	1	1	1	3
<b>3</b>	1	1	3	2	2	4	2	2	1	0
12	1	2	0	1	1	0	0	2	1	0
01	1	2	0	0	0	0	1	1	1	0
0	2	1	0	2	2	0	2	0	2	3

#### 5.3.3. Level II – indicative assessment of the level of competency on the basis of competency matrix developed

A competency matrix analysis can be easily done if there are only a few workers. When the number of them is larger, such as analysis in significantly impeded because of the great number of data. Based on the work [2], it is proposed to introduce a indicative assessment of the maintenance workers' competencies as:

- 1. The total indicator of a competency assessment for a particular worker  $(W_{kc})$ .
- 2. The indicator of workers' competency in a given area (one chosen activity or one type of an operated machine)  $(W_{ko})$ .

The total indicator of a worker's competency  $(W_{kc})$  describes a level of each worker competency for all the realized activities, both in machines operation as well as their supervision. The indicator should be calculated from the formula (1).

$$W_{kc} = \frac{\left(\sum \boldsymbol{D}_0 \cdot \boldsymbol{0}\right) + \sum \boldsymbol{D}_1 \cdot \boldsymbol{1} + \sum \boldsymbol{D}_2 \cdot \boldsymbol{2} + \sum \boldsymbol{D}_3 \cdot \boldsymbol{3} + \sum \boldsymbol{D}_4 \cdot \boldsymbol{4}}{\sum \boldsymbol{D}_n \cdot \boldsymbol{4}} \cdot 100\% \quad (1)$$

where:

- $W_{kc}$  is an indicator of one worker's competency,
- $D_o$  an aggregate number of activities for which a worker possesses 0th level competency ( $D_o$  parameter was put into brackets because there is no need to write it in the formula, however it should be remembered that it has influence on  $D_n$  parameter and at the same time on the  $W_{kc}$  indicator result),

- $D_1$  an aggregate number of activities for which a worker possesses 1st level competency,
- $D_2$  an aggregate number of activities for which a worker possesses 2nd level competency,
- $D_3$  an aggregate number of activities for which a worker possesses 3rd level competency,
- $D_4$  an aggregate number of activities for which a worker possesses 4th level competency,
- $D_n$  a number of all specified activities in total.

It was assumed that  $W_{kc}$  indicator value must be larger than 60 ( $W_{kc}$  > 60%). Such a border value was adopted based on the author's experience and the requirements of the analysed enterprise.

Using the matrix (table 3), a number of activities for which a worker possesses the adequate level of competency was determined. For instance: worker 1 doesn't possess competencies on the level 0, possesses one competency on the levels 1 and 2, five competencies on the level 3 and four competencies on the level 4. Using the formula (1), the value of  $W_{kc}$  competency indicator for particular workers in the analysed enterprise was determined (Tab. 5).

The analysis of the obtained results shows that only 2 out of 6 workers fulfil competency requirements -  $W_{kc} > 60\%$ . The remaining workers have to undergo additional trainings. In order to determine the scope of these trainings, a competency analysis in the chosen area should be conducted (one chosen activity or one type of operated machines) ( $W_{ko}$ ).

The indicator of the workers' competency level (a maintenance team) totally in relation to a given activity should be calculated from the formula (2):

$$V_{ko} = \frac{\left(\sum P_0 \cdot 0\right) + \sum P_1 \cdot 1 + \sum P_2 \cdot 2 + \sum P_3 \cdot 3 + \sum P_4 \cdot 4}{\sum P_n \cdot 4} \cdot 100\% \quad (2)$$

where:

ı

- $W_{ko}$  a competency indicator of a team within a given activity,
- $P_0$  a number of activities with workers possessing 0th level competency (P<sub>o</sub> parameter was put into brackets because there is no need to write it in the formula, however it should be remembered that it has influence on  $P_n$  parameter, and at the same time on the  $W_{ko}$  indicator result),
- $P_1$  a number of workers with the 1st level competency,
- $P_2$  a number of workers with the 2nd level competency,
- $P_3$  a number of workers with the 3rd level competency
- $P_4$  a number of workers with the 4th level competency,

Worker	Numbe	Competency indicator				
	0 ⊕	$\oplus_1$	<b>D</b> <sub>2</sub>	<b>9</b> 3	<b>•</b> 4	W <sub>kc</sub> [%]
Worker 1	0	1	1	5	3	75
Worker 2	2	1	2	3	2	55
Worker 3	3	1	2	2	2	47
Worker 4	2	1	2	3	2	62
Worker 5	5	1	1	3	0	32
Worker 6	3	1	0	2	4	57

Table 5.	The values	of W	<sub>kc</sub> indicator ii	n the	analysed	company
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 $P_n$  – an aggregate number of workers (a maintenance team) being assessed.

Furthermore, it was assumed that the indicator values are  $W_{ko} > 60\%$ .

Table 6 presents the established values of the competency indicator  $W_{ko}$  for particular activities of the assessed maintenance team in the analysed enterprise.

Analysing the results it can be noticed that 6 out of 10 of the assessed activities take the value under 60%. It means that in these areas a competency gap appears. The lowest assessed area is the maintenance of type 1 machines and fulfilling the repairs and defects cards – 42%, and for these areas, in the first place, a training should be organized. In order to identify training needs for particular workers, the assessment results presented in tables 3, 5 and 6 should be considered. In addition, in order to determine training needs the following assumptions were made:

- 1. In the first place, workers and the areas for which the value of competency indicators  $W_{ko}$  and  $W_{kc}$  value is lower than 60% were identified,
- 2. It was assumed that there should be at least one worker with the competency level 4 and minimum two workers with the competency level 3 in every area,
- 3. If the assumption 2 is met in a given area, and the competency indicator value is lower than 60%, the workers with the lowest competency level in a given area, are to be trained in the first place.

Table 6. The values of  $W_{ko}$  indicator in the analysed company

Table 7 presents a proposal of training needs after taking into consideration the established assumptions.

The presented analysis explicitly determines which worker in which area should be trained. In the first place, training needs for the areas and workers with the lowest competency levels should be realized. Thanks to such a solution, it will be possible to provide highly qualified staff in every maintenance area that is being realized. Workers' competencies will be increased ensuring that tasks performance will fulfil the specified standards and will guarantee the right exploitation of devices and machines.

#### 5.3.4. Level III: Assessing the risk of providing a competency level

The identification of a competency gap in an enterprise in many cases is related to the provision of adequate financial resources for their supplementing. In practice, it is very difficult, particularly, for small companies. Thus, what is important is the possibility of the assessment of not providing an adequate competency level of maintenance workers, and, at the same time, of the incorrect realization of a maintenance process. That is why, it is essential to design a risks matrix together with an effective analysis of a risk assessment process in order to optimize resources provision. It is proposed to design such a risk matrix on the basis of  $W_{ko}$  indicator values in relation to the consequences (machine availability -A and the Mean Time Between Failures -MTBF) that may appear at the wrong level of the competencies provision. Table 8 shows a designed risk matrix. The matrix shows at which values of  $W_{ko}$  indicators, the risk of not providing the right level of machine availability (A) and MTBF changes in relation to the realized activities (areas). The matrix identifies 5 risks levels (from very low - VL to very high - VH). It was designed on the basis of the author's experience, the data from the analysed company and with the support of a maintenance expert.

If the values of  $W_{ko}$  and *MTBF* as well as *A* indicators are in the middle of each range, there is no problem in estimating the risk. However, if these values are at the borders of the ranges, there is a possibility of a subjective assessment of the risk level. What's more, the analysis results may influence such uncertainty depending on the

		Macl	nines				Ac	tivities			
Competency levels	Machines operation type 1	Machines operation type 2	Machines operation type 3	Machines operation type 4	Replacement and replenishment media	Machine inspection	Reaction to basic failures	Machine maintenance	Fulfilling the repairs and defects cards	Vibration measurement	
Level 4	2	3	3	3	3	3	4	1	4	4	
Level 3	4	1	3	0	2	3	0	2	3	4	
Level 2	1	4	3	0	3	4	0	2	2	0	
Level 1	0	2	4	2	4	3	3	3	1	0	
Level 0	0	2	0	3	0	3	1	3	0	0	
Competency indicator W <sub>ko</sub> [%]	42	52	71	58	50	67	46	67	42	50	
Average value [%]		5	7		53						

490

Table 7. Proposals of trainings.

			Ma	chines				Acti	vities			
Worker	Competency indicator W <sub>kc</sub> [%]	Machines operation type 1	Machines operation type 2	Machines operation type 3	Machines operation type 4	Replacement and replenish- ment media	Machine inspection	Reaction to basic failures	Machine maintenance	Fulfilling the repairs and defects cards	Vibration measurement	Average value
Worker 1	75%											
Worker 2	55%		+		+			+				1
Worker 3	47%	+			+			+		+	+	
Worker 4	62%											55
Worker 5	32%	+				+				+	+	
Worker 6	57%		+			+				+		
Competency indicator	• W <sub>ko</sub> [%]	42	58	71	58	50	67	46	67	42	50	
Average value [0/]			57	7				53				
Averuge value [	70]					54						

Table 8. The risk assessment matrix

	ş	e)	Consequences									
	ence	iable	Linguistic values	VH	Н	М	L	VL				
	nbəsu	ive var	MTBF [h]	>800	600 - 800	400- 600	200-400	<200				
	Co Co		A (%)	80 to 100	60 to 80	40 to 60	20 to 40	< 20				
	W <sub>ko</sub> %	Des	Risk level	1	2	3	4	5				
-	>80	VH	1	VL	VL	VL	VL	VL				
leve	>60	Н	2	M-L	M-L	L	L	L				
ncy	>40	М	3	M-H	M-H	М-Н	M-L	M-L				
ompete	>20	L	4	VH	VH	н	н	н				
Ŭ	≤20	VL	5	VH	VH	VH	VH	VH				
			Risks: VH= very high; H = high; M-H = medium to high; M- medium; M-L = medium to low; L = low; VL = very low									

available information, knowledge and experience. In these circumstances it is possible to use fuzzy inference based on logic. In this context, the matrix of the risk assessment will be used as the basis for developing the rules for fuzzy inference.

This work presents Mamdani – type fuzzy inference. It is possible to select appropriate membership functions and, with the support of experts, determining the values of these functions within the adopted ranges. The values of  $W_{ko}$  and MTBF as well as A indicators will constitute the input into the system of fuzzy inference in order to calculate the risk level. The analysed case will present the determination of the values of the risk level which is supported by fuzzy logic for  $W_{ko}$  and availability (A) indicator. Input and output parameters are expressed in the quantitative, qualitative and linguistic values. Membership functions described by the formula [3] were adopted for modelling. This function, as presented in works [7, 20, 28], was used

in order to minimize the discrepancy between the reality and mathematical modelling:

Gaussian
$$(x; c, \sigma) = e^{\frac{-(x-c)^2}{2\sigma^2}}$$
 (3)

where c is the centre,  $\sigma$  describes the width of a membership function. "Gauss2mf" function, which is available in MATLAB (R2012) programme, was used for modelling [15, 16]. The function described by the formula (4) is a combination of two parameters (c,  $\sigma$ ) [15]:

$$y = gauss 2mf \left\{ x, \left[ \sigma_1 c_1 \sigma_2 c_2 \right] \right\}$$
(4)

MATLAB (R2012) tool was used for performing the proposed process of fuzzy inference [16]. Fig. 5 presents a fuzzy interference model.



Fig. 5. Fuzzy logic model

Fig. 6 presents some rules which were designed based on table 8.



Fig. 6. Inference rules

Fig. 7, 8, 9 present membership functions for  $W_{ko}$ , availability (A) and a risk level.





Fig. 8. GCMF of A



Input	VL	L		М	Н	VH
A, W <sub>ko</sub>	[5 0 5 10]	[5 30 5 30]		[8 50 8 50]	[5 70 5 70	[5 90 5 100]
Output	VL	L	M-L	M-H	н	VH
-						



Table 9 presents the adopted values of Gaussian membership function at input and output.

Figure 10 presents inference rules and the example of determining the risk level of the consequences of not providing an adequate competency level for the realization of supervision activities over machines and devices.



Fig. 10. Risk level calculation

The calculation of the risk level was conducted for  $W_{ko}$  indicator value  $W_{ko} = 50$  and D=50. The risk was assessed at the level = 3. The centroid method was used as a defuzzification method. Rule 8 is the strongest in action. It means that the risk of sustaining machine availability on the level 50, at such a competency level, is described as medium.

This analysis will allow to determine on which level a competency indicator should be maintained in order to minimize the risk of its influence on efficiency and effectiveness of the realized in maintenance.

#### 6. Summary and conclusions

Effectiveness of a maintenance process in an enterprise requires competent and aware workers. The study results presented in the first part of the work showed that companies are aware of the need of the maintenance workers' competency assessment. In many companies, these assessments are realized, and on their basis conclusions are

drawn and improvement action is undertaken. Many companies, particularly small, do not carry out such actions. That's why, presented the second part of the work, the threelevel methodology of workers' competency assessment and the example of its use in the given enterprise may help such companies in the selection of an adequate competency assessment. The use of an adequately selected method of a competency assessment shall allow to: identify a current level of competencies, but, most of all, to identify the training needs, in order to improve efficiency and effectiveness of the maintenance process realization.

The proposed work has some limitations due to the fact that the method was verified in one company only. That's why, in the further work, this method will be verified in other companies as well. The results of this verification will allow to identify the limitations deriving from companies functioning and to identify additional essential requirements, which the assessment should take into account.

References

- 1. Abele E, Reinhart G. Zukunft der Produktion, München: Hanser, Carl, 2011.
- Baron Puda M. Projektowanie strategii rozwoju kompetencji pracowników przedsiębiorstw produkcyjnych. Zarządzanie przedsiębiorstwem 2012; 4: 2-11.
- 3. Bokrantz J, Skoogh A, Berlin C, Stahre J. Maintenance in digitalised manufacturing: Delphi-based scenarios for 2030. International Journal of Production Economics 2017: 191: 154-169.
- 4. Dalkilic S. Improving aircraft safety and reliability by aircraft maintenance technician training. Engineering Failure Analysis 2017; 82: 687-694, https://doi.org/10.1016/j.engfailanal.2017.06.008.
- 5. Furman J. Poprawa skuteczności utrzymania maszyn w przedsiębiorstwie produkcyjnym studium przypadku. Komputerowe Zintegrowane Zarządzanie, 2016:548-557.
- Gonczi A, Hager P, Athanasou J. The Development of Competency-Based Assessment Strategies for the Professions National Office of Overseas Skills Recognition, Australia: 1993.
- 7. Greenstein L. Assessing 21st century skills: A guide to evaluating mastery and authentic learning SAGE: 2012.
- 8. Hameed A. Using Gaussian membership functions for improving the reliability and robustness of students' evaluation systems. Expert Systems with Applications 2011; 38(6): 7135–7142, https://doi.org/10.1016/j.eswa.2010.12.048.
- Herterich M, Uebernickel F, Brenner W. The Impact of Cyber-Physical Systems on Industrial Services in Manufacturing. Procedia CIRP 2015; 30: 323-328, https://doi.org/10.1016/j.procir.2015.02.110.
- Hertlea C, Tischa M, Kläsa H, Metternicha J, Abelea E. Recording Shop Floor Management Competencies A Guideline for a Systematic Competency Gap Analysis. Procedia CIRP 2016; 57: 625 – 630, https://doi.org/10.1016/j.procir.2016.11.108.
- Jasiulewicz-Kaczmarek M, Drożyner P. Preventive and Pro-Active Ergonomics Influence on Maintenance Excellence Level, [in.] M.M. Robertson (eds.) Ergonomics and Health Aspects, HCII 2011, LNCS 6779 Springer-Verlag Berlin Heidelberg, ISBN 978-3-642-21715-9 2011; 49-58.
- Jasiulewicz-Kaczmarek M, Saniuk A, Nowicki T. The maintenance management in the macro-ergonomics context. [in.] Richard H.M. Goossens (eds.) Advances in Social & Occupational Ergonomics Proceedings of the AHFE2016 Conference on Social & Occupational Ergonomics, July 27-31, Walt Disney World®, Florida, USA Series: Advances in Intelligent Systems and Computing 2016; 487:35-46, https://doi.org/10.1007/978-3-319-41688-5.
- 13. Kaufhold M. Kompetenz und Kompetenzerfassung.VS, Verl Für Sozialwiss, 2006.
- Loska A. Scenario modeling exploitation decision-making processes in technical network systems. Eksploatacja i Niezawodnosc Maintenance and Reliability 2017; 19 (2): 268–278, https://doi.org/10.17531/ein.2017.2.15.
- 15. Mathworks. Fuzzy inference system modelling: Gaussian combination membership function, 2014. available: http://www.mathworks.se/ help/fuzzy.
- 16. Matlab, MATLAB 7 12 0 (R2011a), Fuzzy logic Toolbox, 1984–2014 The MathWorks, Inc , 2014.
- 17. Misiurek B. Metodyka standaryzacji autonomicznych działań eksploatacyjnych zorientowana na poprawę efektywności maszyn zautomatyzowanych, Praca doktorska, Uniwersytet Technologiczny we Wrocławiu, 2015.
- Muller A, Marquez A C, Iung B. On the concept of e-maintenance: Review and current research. Reliability Engineering and System Safety 2008; 93:1165-1187, https://doi.org/10.1016/j.ress.2007.08.006.
- Müllera R, Vette M, Geenen A. Skill-based dynamic task allocation in Human-Robot-Cooperation with the example of welding application. Procedia Manufacturing 2017: 13 – 21.
- 20. Paśkiewicz J. Doskonalenie procesu nadzoru maszyn na przykładzie wybranego przedsiębiorstwa, diploma thesis under supervising K. Antosz, Rzeszów, 2016.
- 21. Pellegrino J, Justiniano M, Raghunathan A. Measurement Science Roadmap for Prognostics and Health Management for Smart Manufacturing Systems, NIST Advanced Manufacturing Series 2017; 191: 154-169.
- 22. Pittich D. Diagnostik fachlich-methodischer Kompetenzen, Fraunhofer IRB Verl, 2013.
- Ratnayake RMC. Knowledge based engineering approach for subsea pipeline systems FFR assessment: A fuzzy expert system. The TQM Journal 2016; 28:40–61, https://doi.org/10.1108/TQM-12-2013-0148.
- 24. Rodriguez D, Patel R, Bright A, Gregory D, Gowing M K. Developing competency models to promote integrated human resource practices. Human Resource Management 2002; 41(3): 309-324, https://doi.org/10.1002/hrm.10043.
- 25. Roy R , Stark R, Tracht K, Takata S, Mori M. Continuous maintenance and the future Foundations and technological challenges. CIRP Annals -Manufacturing Technology 2016; 65: 667-688. https://doi.org/10.1016/j.cirp.2016.06.006
- 26. Schlick C, Bruder R, Luczak H. Arbeitswissenschaft. 3. Auflage Springer-Verlag, 2010, https://doi.org/10.1007/978-3-540-78333-6.
- 27. Sherwin D J. A review of overall models for maintenance management Journal of Quality in Maintenance Engineering 2000; 1(1): 15-19, https://doi.org/10.1108/13552519510083101.

The implementation of this method is time-consuming. It needs collecting certain information, not only related to workers but also machines, e.g. MTBF indicator, what in many companies, particularly small ones, is organisationally difficult. Therefore, further works should try to support the process of the workers' assessment with the use of the data collected in CMMS systems. That would allow to obtain the needed information and, at the same time, to facilitate the process of the workers' assessment.

- 28. Shingo S. Study of "Toyota" Production system from industrial engineering viewpoint Tokyo: Japan Management Association, 1981.
- 29. Smith R, Mobley R K. Maintenance Skills Assessment, Industrial Machinery Repair 2003: 26–49, https://doi.org/10.1016/B978-075067621-2/50003-2.
- 30. Stadnicka D, Arkhipov D, Battaia O, Ratnayake RMC. Skills management in the optimization of aircraft maintenance processes. IFAC PapersOnLine 2017; 50(1): 6912–6917, https://doi.org/10.1016/j.ifacol.2017.08.1216.
- 31. Tay K M, Lim C P. On the use of fuzzy inference techniques in assessment models: part II: industrial applications. Fuzzy Optimization and Decision Making 2008; 3:283–302, https://doi.org/10.1007/s10700-008-9037-y.
- 32. Wirkus M, Drozd R, Bielski R. Production employees competence in apparatus processes. Management Forum 2015; 3(30:63-70.
- 33. Zio E. Reliability engineering: Old problems and new challenges. Reliability Engineering & System Safety 2009; 94:125-41.

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### SELECTING OPERATING PARAMETERS OF AN ELECTROSTATIC PRECIPITATOR DECREASING EMISSION OF SOLID FUELS FLY ASHES

# DOBÓR PARAMETRÓW EKSPLOATACYJNYCH ELEKTROFILTRU OBNIŻAJĄCEGO NISKĄ EMISJĘ PYŁÓW POCHODZĄCYCH ZE SPALANIA PALIW STAŁYCH\*

The article presents the results of research aimed at developing the construction of an ESP (electrostatic precipitator), as well as the performance and selection of operating parameters of the ESP for household applications. The object of the experiment was the ESP prototype, designed and made by the authors, assigned to be placed in a gas pass of a detached house. A simulation of dustiness caused by burning solid fuels has been done. The experiment has been carried out for two different degrees of dust concentration at the ESP inlet, by controlling the given voltage. The results proved that the proposed constructional solution of the ESP significantly limits low emission PM2.5 and PM10 dust emitted during the process of burning solid fuels: coal and/or biomass in boilers and fireplaces used in households or in small local boiler houses.

*Keywords:* air protection, low emission, PM10 and PM 2.5 dust, electrostatic precipitator, operating parameters.

W artykule przedstawiono wyniki badań, mających na celu opracowanie konstrukcji, wykonanie oraz dobór parametrów eksploatacyjnych elektrofiltru do zastosowań w gospodarstwach domowych. Obiektem badań był opracowany i wykonany przez autorów prototyp elektrofiltru przeznaczony do montażu w kanale spalinowym budynku jednorodzinnego. Istotnym problemem jest dobór odpowiedniej elektrody ulotowej. Zasymulowano zapylenie powstające na skutek spalania paliw stałych. Badania przeprowadzono dla dwóch różnych stężeń pyłów na wlocie do elektrofiltru, regulując podawane napięcie. Uzyskane wyniki wykazały, że przyjęte rozwiązanie konstrukcyjne elektrofiltru umożliwia znaczne ograniczenie niskiej emisji pyłów PM2,5 i PM10 emitowanych w procesach spalania paliw stałych: węgla kamiennego i/lub biomasy w kotłach lub kominkach stosowanych w gospodarstwach domowych lub małych kotłowniach lokalnych.

Slowa kluczowe: ochrona powietrza, niska emisja, pyły PM10 i PM2,5, elektrofiltr, parametry eksploatacyjne.

#### 1. Introduction

Suspended dust pollution in the air seems to be a crucial problem widely influencing on the environment and the society heath due to lead, cadmium, nickel and arsenide compounds migration, together with toxic dust. One of the sources of air pollution is dust produced during burning solid, liquid and gas fuels emitted to the atmosphere. Another reason of air pollution is dust occurring as exhaust gases as a consequence of using vehicles, burning diesel fuel in spontaneous ignition engines and abrasion of mechanical elements e.g. braking systems [4, 5]. Sources placed on height lower than 40 metres are called low emission ones. Low emission is the source of many kinds of pollution, among others PM10 and PM2.5 dusts. Those fractions contain, among others: polycyclic aromatic hydrocarbons, dioxins and heavy metals or their compounds [20]. The problem of exceeding air purity standards with suspended dust coming from low emission sources affects both big urban agglomerations and small towns (including heath resorts).

In towns with poor natural ventilation, resulting from geographical features or land development limiting natural ventilation ducts of building areas, low emission is the main factor causing smog.

The air pollution problem has been a subject of analyses carried out by European Environment Agency (EEA) for many years [8]. Their reports indicate for Poland as one of leading countries facing problems especially with suspended dust, occurring mainly by solid fuel combustion. The highest number of days with exceeded standards of PM10 fraction is observed in Bulgaria.

Examinations carried out as a part of international project Aphecom in cooperation with European Thematic Centre on Air and Climate Change (ETC/ACC) showed that increase in morbidity caused by air pollution with PM10 and PM2.5 dust generates additional costs of medical care by 31 billion € in the countries which are members of UE [3, 16].

European Parliament and European Council's guidance 2008/50/WE published on  $21^{st}$  May 2008, referring to the quality and purity of air for Europe, points at the problem of air pollution (CAFE) [7]. This guidance forces the UE members to take corrective actions in places where exceeding acceptable pollution levels, particularly PM10 and PM2.5 and CO<sub>2</sub>, have been noted.

A significant exceeding of suspended dust concentration standards seems to be a serious problem in Poland. According to EEA report from 2017, the amounts of premature death caused by exposition to MP2.5 dust equals 41 300 cases [8]. In big agglomerations and towns where detached

(\*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

houses mostly occur, the process of burning low quality coal in household furnaces, fireplaces, local boiler houses are one of the most important sources of low emission dust and harmful gases. Biomass in form of granules (pellets) or burning wood are also a popular source of energy used in households. Physical, chemical and electrical qualities as well as grain composition of dust produced from burning biomass are extremely diversified depending on the kind of fuel and its humidity [19, 21].

Those fuels are often burnt in outdated boilers. It results from economic reasons. In recent years a system of bonuses has been introduced in Poland in order to encourage the users of outdated boilers and furnaces to replace them with new appliances. A big effort to enable as big as possible number of individual users the access to urban heating network has been done. Howev-

er, all these activities tend to be long-lasting. Nowadays experiments on underground gasification are being carried out. Gas produced this method used as energy carrier will make possible to limit the emission of suspended dust formed during burning coal [14].

One of methods limiting air pollutants emission, particularly PM10 and PM2.5 fractions, is introducing an easy in usage ESPs which can be applied in households and local boiler houses equipped with a boiler of energy power up to 40 kW. Tests of this kind of devices, varying in construction solutions are being carried out by science centres [9, 18] as well as commercial products manufacturers [10] (OekoSolve - Switzerland, RWE Aktiengesellschaft - Germany, Ruff-Kat GmbH Holzkirchen - Germany, Zumikron Rüegg - Switzerland). In Department of Manufacturing Systems AGH University of Science and Technology such experiments have also been undertaken. They resulted in developing a construction of an ESP designed to be placed in a detached house's gas pass. The ESP limits dust pollution emission occurring during the process of burning solid fuels to the level below the one recommended in The European Council Guidance 2015/1189 [6] which estimates maximum solid particles emission in the in solid fuel automatically supplied boilers at 40 mg/m<sup>3</sup>.

#### 2. Examination method

#### 2.1. Physicochemical properties of dusts

Physicochemical properties of dust from fuel combustion affect the choice of a constructional solution and the ESP electric parameters [12, 13]. Examination of a dedusting gas-dust aerosol process has been carried out for dust produced from burning coal and biomass. They are typical solid fuels used as heating energy carriers in households and local boiler houses.

While examining dust, particular physical and chemical qualities, essential in the process of electrostatic exhausted gases dedusting, have been defined:

- relative density (pycnometer method),
- humidity (gravimetric method),
- flammable parts content (gravimetric method),
- grain composition (Mastersizer 2000 Malvern Instruments Ltd. analyzer),
- dust layer resistivity (high voltage direct current method),
- dust layer breakdown voltage (high voltage direct current method).

#### 2.2. ESP test stand

The examination of the dust grains separating process has been done in a laboratory ESP made of alloy steel H17N13M2. Technical parameters of the ESP:

- chamber diameter ø150 mm,
- active length 1000 mm,
- discharge corona electrode exchangeable electrodes of varied contours and emissivity,
- variable-capacity dust feeder,

- air flow through the chamber generated by a centrifugal fan of changeable efficiency, providing the ability to change the flow velocity ranging from 1-10 m/s,
- supplying circuit: 1-phase 230 V AC, high voltage 10-70 kV DC, current  $I \le 2 \text{ mA}$ ,
- controlling-measuring circuit and purifying collecting electrode executive circuit.

During the experiment following measurements have been made: carrier (air) flow velocity through the ESP chamber, discharge electrode supply voltage, dust presence at the ESP outlet (using triboelectric dust meter) as well as its concentration measured by gravimetric method. A view of the laboratory ESP is shown in Figure 1.



Fig. 1. The view of a laboratory ESP

The elements of the laboratory stand have been shown according to the tags in Figure 2. A centrifugal, mono-phase fan (1), supplied by the thyristor voltage regulation unit for inductive load of TPR-2N type provides the air flow through the ESP chamber. Using the regulation unit enables air flow velocity change ranging from 1-10 m/s.

In the inlet part (reducing pipe) of the ESP a variable-capacity dust feeder (2) has been placed. A stepping motor, its controller and a changeable frequency steering generator provide dust amount modified in a time unit. A nozzle (3) to additional compressed air loading from a compressor for low velocity of air flow in the ESP has been designed. This enables a better gas-dust aerosol producing process. The dust placed on the collecting electrode, after removing by rapping system is gathered in the container (4). In the upper (vertical) part of the ESP a junction box with an insulation board and a handle to replace discharge electrodes has been installed. There is a centrally placed discharge electrode inside the ESP



Fig. 2. Simplified diagram of the laboratory ESP 1 - fan, 2 - dust feeder, 3 - compressed air nozzle, 4 - separated dust container, 5 - lower discharge electrode holder, 6 - discharge electrode, 7 - upper discharge electrode holder, 8 - dust meter sensor, 9 - air flow velocity sensor, 10 - air flow measurement circuit, 11 - dust concentration measurement circuit, 12 - high voltage measurement, 13 - ESP current measurement.

chamber (5). A thick-walled pipe made of dielectric material, with a dust meter probe (6) and air flow velocity measurement unit (7) have been placed at the outlet of the ESP. Additionally, a system to purify the chamber from the dust deposited on its surface, enabling periodical removing it from the collecting electrode, has been designed.

Electric circuits of the stand consist of: discharge electrode high voltage supplier, high voltage measurement (11) and ESP current circuits (12). Air flow velocity through the ESP chamber is measured on-line with a measurement turbine (7) with a Hall effect sensor. Presence of the dust at the ESP outlet is recorded with the usage of a triboelectric dust meter. Voltage signals from the measurement circuits of the discharge electrode supplying voltage, current flowing between the collecting electrode and the circuit mass as well as the signal from the dust meter outlet were sent to data acquisition NI-USB6039 card. A measurement card working at sampling frequency of 1 kHz recorded averaged value of measured voltages. The data collecting program, working as a virtual XY recorder, enables recorded data visualization on-line. The data have been recorded in ASCII files in order to complete their further analysis.

#### 2.3. The discharge of the electrode parameters selection

A tubular ESP designed for a household usage has only one discharge electrode, placed centrally in the chamber. The selection of its electric parameters has a crucial importance in a proper run of the exhausted gases dedusting process.

Basic criterion of the ESP discharge electrode parameter selection is providing such conditions that dust grains introduced into the ESP chamber could receive electric charge to make them migrate and deposit on the collecting electrode [2, 11]. Transmitting electric charge from gas ions to the dust grains plays the main role. Their source are phenomena occurring in the nearest surrounding the discharge electrode, more precisely, from the points on its surface where electron avalanche starts. The process of electric charge gathering by the dust grains in the area between electrodes can be described as their taking up electric charge. Electrically charged dust grains move mostly towards the collecting electrodes. The majority of dust grains are negatively charged and deposit on the grounded collecting electrodes of positive potential [15], when the resistivity of the dust layer placed on the collecting electrode significantly affects its characteristic [1].

The selection of the ESP discharge electrode type and its properties for household usage has been realized based on the basis of determined current-voltage characteristics of chosen discharge electrodes and discharge initial voltage.

Current-voltage characteristic I-U can be obtained by recording flowing current change in the area between electrodes as a function of discharge electrode supplying voltage. Measurements have been done changing discharge electrode supplying voltage in the range U=0-30 kV. The collecting electrode is connected to the positive end of the supplying system through a 0.05% tolerance decadal resistor. Recording the discharge electrode supplying voltage values and the current flowing in the inter-electrode space, proportionally to the voltage fall in the decadal resistor enables determining I-U characteristic. Voltage signals from discharge electrode supplying voltage measurement circuits as well as current flowing between the collecting electrode and the circuit mass are sent to the data acquisition card NI-USB 6039, connected to a computer equipped with data recording software. For each measuring point, at  $\Delta U$ =500V step, an averaged value of measured voltage has been recorded. The recorded data have been filed in order to be analyzed further.

*ent,* The initial voltage of the discharge electrode has been determined as a linear function U/I=f(U) (reduced characteristic). The current-voltage characteristic of the discharge electrode and the initial corona voltage are the proof of the electrode emissivity, consequently, the ability to generate electrostatic field, where the dust grains can receive electric charge.

#### 3. Examination results

Selected physical and chemical properties influencing significantly the electrostatic process of separating dust from the coal and biomass combustion have been shown in Table 1.

Physicochemical properties		Unit	Fly ash from combus- tion	
- 1.jorooononioon pr	operates	0	Coal	Biomass
Relative density		kg/m <sup>3</sup>	1902.0	2400.0
Moisture content		%	0.42	1.15
Flammable parts content		%	5.933	3.31
Du at laura a ai ativita	30°C	Ω/cm	$1.4 \cdot 10^{8}$	$1.1 \cdot 10^{10}$
Dust layer resistivity	150°C	Ω/cm	$1.1 \cdot 10^{11}$	$1.3 \cdot 10^{11}$
Dust layer breakdown voltage		kV/mm	0.995	0.976

 Table 1. Physicochemical properties of fly ashes from coal and biomass combustion

The compilation of the grain composition analysis results made with Mastersizer 2000 has been shown in Figure 3. The results indicate that the content of PM2.5 and PM10 grain fraction in dust do not exceed 20 vol%.

The selection of the ESP discharge electrode has been done by analyzing current-voltage characteristic and the discharge electrode initial corona voltage. It was established that the tabular ESP discharge electrode designed for a household usage should be characterized by high emissivity, possibly low initial corona voltage and high mechanic durability. Due to that reason, the usage of wire electrode in the ESP has been given up (so far popular in many solutions) [17]. During the process of selecting discharge electrode, it has been as-



Fig. 3. The granulometric distribution of fly ashes from coal and biomass combustion

sumed that mast electrodes will be a much better construction. Owing to their rigidity, they can be successfully placed in ESP chamber by means of mono-point fixing from the top, which simplifies the ESP construction and eliminates the probability of short-circuit on conducting bridges of dust, which could deposit on the lower fitting element of the discharge electrode.

The emissivity measurement results for selected electrodes have been shown in Figure 4.



Fig. 4. Current-voltage characteristic of discharge electrodes

The analysis of the results proved that the construction of a mast spike type electrode supposed to be modified to receive better electric parameters. The measurements confirmed the correctness of such a solution. A mast electrode "A" typed is characterized by very high emissivity and low initial corona voltage  $U_0$ =5,7 kV.

Some initial assumptions have been done concerning the process of dedusting exhaust gases produced from solid fuels (coal and biomass) burning in fireplaces and heating boilers. Those assumptions referred to power of the applied boiler, sorts and properties of solid fuels, efficiency of dust separation by the ESP, simplicity of the constructional solution, minimizing its building and operating costs. Estimating the ESP efficiency of the dust separating, it has been defined that the dust concentration at the ESP outlet should not exceed  $40 \text{ mg/m}^3$ , was indicated in UE guideline 2015/1189 [6].

Taking under consideration the diversity of energy boilers operating in households, their technical state as well as parameters of fuels burnt in them, there is no possibility to define unmistakably the quality (physical and chemical dust properties) and the quantity (flow velocity, dust concentration at the boiler outlet) parameters of purified exhaust gases. In such case the most disadvantageous dedusting parameters should be accepted. Consequently, to reach the amount of dust aerosol which is necessary to obtain carrier flow velocity 1.0 m/s and 1.5 m/s assumed a concentration at the ESP inlet:

- 2000 mg/m<sup>3</sup> of air,
  - 4000 mg/m<sup>3</sup> of air.

Dust separating efficiency by the ESP dust concentration was 7 to 12 times higher comparing to the calculated dust con-

centration for given boiler heating power and calorific value of fuels. Also the assumed carrier flow velocity through the ESP chamber was about twice higher than the one defined in calculations. A series of measurements changing the air flow velocity in the ESP chamber, dust concentration and discharge electrode supply voltage was carried out.

During the examination of the dedusting process the ESP operating current change has been defined as a function of the supply voltage for chosen dust concentration values at given velocity of the gasdust aerosol flow through the chamber. The relationship between the value of the ESP inter-electrode current and the discharge electrode supply voltage has been shown in Figure 5.



Fig. 5. The relationship between ESP current and the discharge electrode supply voltage

The ESP current measurements results proved a slight effect of dust concentration and the carrier flow velocity onto the current values. The current changes in the whole range of dust concentration changes and the carrier velocity have not exceeded 10%. It means that the ESP current depends mainly on its contours, the discharge electrode supply voltage and the current efficiency of the high voltage supplier.

On the basis of carried out measurements, the change of dust concentration at the ESP outlet has been defined as a function of the discharge electrode supply voltage. The results received for dust produced from coal and biomass combustion have been shown in Figure 6 and Figure 7.

The most important operating parameter for the ESP is a dedusting efficiency. Gaining high efficiency by the ESP confirms a proper selection of its geometrical features adjusted during the designing process. A correct selection of features has an influence on the discharge electrode parameters, as also the effectiveness. A selection of a high voltage supplier, its output voltage and current efficiency are also important. The results of coal and biomass fly ashes dedusting





Fig. 6. The relationship between coal fly ash concentration at the ESP outlet and the discharge electrode supply voltage



Coal fly ash						
	Carrier flow velocity 1 m/s					
ESP Operating volt- age	Dust concentration at the ESP inlet <b>2000</b> [mg/m <sup>3</sup> ]	ESP efficiency	Dust concentration at the ESP inlet <b>4000</b> [mg/m <sup>3</sup> ]	ESP efficiency [%]		
[kV]	Dust concentration at the ESP <b>outlet</b> [mg/m <sup>3</sup> ]	[%]	Dust concentration at the ESP <b>outlet</b> [mg/m <sup>3</sup> ]			
0	500.0	0.0	840.0	0		
5	226.7	54.7	673.3	19.8		
10	26.7	94.7	66.7	92.1		
15	6.7	98.7	20.0	97.6		
30	6.7	98.7	6.7	99.2		
	Carrier flow velocity 1.5 m/s					
ESP Operating voltage	Dust concentration at the ESP inlet <b>2000</b> [mg/m <sup>3</sup> ]	ESP efficiency [%]	Dust concentration at the ESP inlet <b>4000</b> [mg/m <sup>3</sup> ]	ESP efficiency [%]		
[KV]	Dust concentration at the ESP <b>outlet</b> [mg/m <sup>3</sup> ]		Dust concentration at the ESP <b>outlet</b> [mg/m <sup>3</sup> ]			
0	830.0	0.0	1413.3	0.0		
5	700,0	15,7	1260.0	10.8		
10	126.7	84.7	226.7	84.0		
15	40.0	95.2	120.0	91.5		
20	6.7	99.0	33.3	97.6		
30	6.7	99.2	20.0	98.6		

Table 2. ESP efficiency for coal fly ash for chosen values of discharge electrode voltage supply

		Biomass fly ash			
	Carrier flow velocity 1 m/s				
ESP operating voltage	Dust concentration at the ESP inlet <b>2000</b> [mg/m <sup>3</sup> ]	ESP	Dust concentration at the ESP inlet <b>4000</b> [mg/m <sup>3</sup> ]	ESP efficiency [%]	
[KV]	Dust concentration at the ESP <b>outlet</b> [mg/m <sup>3</sup> ]	[%]	Dust concentration at the ESP <b>outlet</b> [mg/m <sup>3</sup> ]		
0	393,3	0,0	773,3	0,0	
5	166,7	57,6	393,5	49,1	
10	6,7	98,3	6,7	99,1	
15	6,7	98,3	6,7	99,1	
30	3,3	99,2	6,7	99,1	
	Carrier flow velocity 1.5 m/s				
ESP operating voltage	Dust concentration at the ESP inlet <b>2000</b> [mg/m <sup>3</sup> ]	ESP	Dust concentration at the ESP inlet <b>4000</b> [mg/m <sup>3</sup> ]	ESP efficiency [%]	
[KV]	Dust concentration at the ESP outlet [mg/m <sup>3</sup> ]	[%]	Dust concentration at the ESP <b>outlet</b> [mg/m <sup>3</sup> ]		
0	666.7	0	1100.0	0.0	
5	440.0	34	753.3	31.5	
10	26.7	96	46.7	95.8	
15	3.3	99.5	6.7	99.4	
30	3.3	99.5	3.3	99.7	

Table 3. ESP efficiency for biomass fly ash for chosen values of discharge electrode voltage supply

efficiency for chosen values of the ESP discharge electrode supply voltage at the carrier flow velocity v=1.0 m/s and v=1.5 m/s have been compared in Table 2.

The analysis of the results presented in Table 2 indicates high ESP efficiency. Accepting the most unfavorable ESP operating conditions e.g. high velocity of flowing exhaust gases and high dust concentration at the boiler outlet, the discharge electrode voltage (for a ø150 mm diameter chamber) should equal about 20 kV. For such voltage, ESP operating current *I* will not exceed 0.5 mA.

The results of analogical ESP efficiency measurement for biomass fly ash are depicted in Table 3.

The analysis of the results indicates that in case of biomass fly ash at the discharge electrode supply voltage  $U \ge 15$  kV, the suspended dust concentration at the ESP outlet is lower than the concentration level recommended by The European Council Guidance (40 mg/m<sup>3</sup>). The measurements results shows above proved effectiveness of separation, both coal and biomass fly ashes, although these dusts have different physicochemical and electrical properties.

#### 4. Conclusion

The experiment and the analysis of the measurements results were aiming at developing an idea of a construction of the ESP and a selection of its geometrical, electrical and processing parameters. This target has been reached, which can be confirmed by the received ESP efficiency. It has been defined the ESP operating parameters providing a proper run of the process of separating solid fuels fly ashes used in households.

The results of verifying examination carried out on a laboratory stand with the usage of coal and biomass fly ashes proved that the ESP separates dust according to the accepted assumptions. It has been confirmed by carrying out a dedusting test in which gas-dust aerosol concentration 12-times exceeded the concentration values resulting from the exploitation of an energy boiler in household conditions. In those tests dust was loaded to the ESP in such quantity to reach 4000 mg/m<sup>3</sup> of its concentration at the outlet. At supply voltage U=20 kV ESP efficiency was equal or greater than 97.6%. It means that selected operating conditions (with the parameters similar to model dust produced from coal and biomass combustion) caused a decrease in dusting from 300 mg/m<sup>3</sup> to values lower than 10 mg/m<sup>3</sup>. Thus, the received results indicate for the correctness of the idea of an ESP construction.

The validation of the ESP constructional solution for households needs required examining the ESP device in real conditions. Due to that fact, the ESP of ø180 mm diameter chamber prototype has been made for household needs. It has been installed in a gas pass in a building heated with an energy boiler DEFRO Optima Comfort 15STD of 15 kW feeds with coal or wood pellets. That ESP has been equipped with a collecting electrode dust deposits dislodged system. It enables a proper run of the dedusting exhaust gases process. The ESP is supplied from one-phase 230V electric network. The supply circuits consist of: a high voltage supplier 30 kV DC, a microprocessor controller supervising ESP operation e.g. conjunction temperature exceeding

the dew-point in the ESP chamber, the time interval of purifying the electrode from dust deposit, the appliance operating state etc. The estimated power consumption at nominal load does not exceed 30W.

The idea of the constructional solution shown above, after further exploitation experiments, will enable production of ESP suitable for individual needs.

### References

- 1. Barranco R, Gong M, Thompson A, Michael Cloke M, Hanson S, Will Gibb W, Lester E. The impact of fly ash resistivity and carbon content on electrostatic precipitator performance. Fuel 2007; 86: 2521–2527, https://doi.org/10.1016/j.fuel.2007.02.022.
- 2. Böttner C U. The role of the space charge density in particulate processes in the example of the electrostatic precipitator. Powder Technology 2003; 135–136: 285–294, https://doi.org/10.1016/j.powtec.2003.08.020.
- 3. Chanem O, Perez L, Knuli N, Medina S. The hidden economic burden of air pollution-related morbidity: evidence from the Aphekom project. Eur .J Health Econ. 2016; 17: 1101, https://doi.org/10.1007/s10198-015-0748-z.
- Chłopek Z. Testing of hazards to the environment caused by particulate matter during use of vehicles. Eksploatacja i Niezawodnosc Maintenance and Reliability 2012; 14 (2): 160–170.
- 5. Chłopek Z Jakubowski A. The examination of the reduction of particulate matter emission from motor vehicle braking systems. Eksploatacja i Niezawodnosc Maintenance and Reliability 2010; 4 (48): 29–36.
- Commission Regulation (EU) 2015/1189 of 28 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for solid fuel boilers, J L 193, 2015; 100–114.
- Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. OJ L 152, 2008; 1–44.
- European Environment Agency. Air quality in Europe 2017 report, EEA Report No 13/2017 Publications Office of the European Union Luxembourg 2017; ISBN 978-92-9213-920-9 doi:10.2800/358908.
- 9. Fischer T, Grass N, Zouzou N, Dăscălescu L, Greil R, Hopf N. Smart home precipitator for biomass-furnaces: Design considerations on a small scale electrostatic precipitator. Annual Meeting. IEEE Transactions on Industry Applications 2014; 50: 2219-2224
- Hartmann H, Turowski P, Kiener S. Electrostatic procipitators for small-scale wodo combustion systems Results from lab-and field tests. Central Europe Biomass Conference (CEBC), 26.-28. January 2011 Graz. IEA Task32-Workshop: "Fine particulate emissions from small-scale biomass furnaces".
- 11. Jędrusik M, Świerczok A. The correlation between corona current distribution and collection of fine particles in a laboratory-scale electrostatic precipitator. Journal of Electrostatics, v. 71, 2013; 3: 199–203
- 12. Machnik R, Karwat B, Nocuń M, Niedźwiedzki J. Wpływ fizykochemicznych właściwości popiołów lotnych ze spalania węgli na proces elektrostatycznego odpylania spalin. Przemysł Chemiczny 2015; 94(9): 1530–1533.
- 13. Machnik R, Nocuń M. Effect of anti-corrosion coatings of corona electrodes on selected operating parameters of industrial electrostatic precipitators. Eksploatacja i Niezawodnosc Maintenance and Reliability 2014; 16(1): 56–60.
- Mocek P, Zamiar R, Jachimczyk R, Gowarzewski R, Świądrowski J, Gil I, Stańczyk K. Selected issues of operating 3 MW underground coal gasification installation. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2015; 17 (3): 427–434, https://doi.org/10.17531/ ein.2015.3.14.
- 15. Parker K. Electrical operation of electrostatic precipitators. London, The Institution of Electrical Engineers 2003.
- 16. Pascal M, Medina S. Résumé des résultats du projet Aphekom 2008-2011. Des clefs pour mieux comprendre les impacts de la pollution atmosphérique urbaine sur la santé en Europe. Saint-Maurice: Institut de veille sanitaire; 2012; 6 p. Disponible à partir de l'URL: http://www. invs.sante.fr.
- 17. Popa G N, Dăscălescu L. Variable Cross-Section Cylinder-Type Corona and Combined Corona–Dielectric Barrier Discharge Precipitators for Fly-Ash Particles. Particulate Science and Technology: An International Journal, Taylor & Francis 2014: 445-450, https://doi. org/10.1080/02726351.2013.878773.
- Ruttanachot Ch, Tirawanichakul Y, Tekasakul P. Application of electrostatic precipitator in collection of smoke aerosol particles from wood combustion. Aerosol Air Qual. Res. 2011; 11: 90-98, https://doi.org/10.4209/aaqr.2010.08.0068.
- 19. Vicente E D, Alves C A. An overview of particulate emissions from residential biomass combustion. Atmospheric Research 2018; 199: 159–185, https://doi.org/10.1016/j.atmosres.2017.08.027.
- 20. Wiinikka H, Grönberg C, Boman C. Emissions of heavy metals during fixed-bed combustion of six biomass fuels. Energy Fuel 2013; 27: 1073-1080, https://doi.org/10.1021/ef3011146.
- 21. Zhang Y, Obrist D, Zielinska B, Gertler A. Particulate emissions from different types of biomass burning. Atmos. Environ. 2013; 72: 27-35, https://doi.org/10.1016/j.atmosenv.2013.02.026.

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