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Automated error logging in the flowmeter design process: Approaches to processing and analysis

Rostyslav Sapeliuk*
Postgraduate Student
Lviv Polytechnic National University
79013, 12 Stepana Bandery Str., Lviv, Ukraine
https://orcid.org/0009-0001-6436-751X

Vitalii Roman
PhD in Technical Sciences, Associate Professor
Lviv Polytechnic National University
79013, 12 Stepana Bandery Str., Lviv, Ukraine
https://orcid.org/0000-0002-8546-6752

Abstract. In the modern design of variable differential pressure flowmeters, the introduction of reliable automated logging systems is relevant, as conventional logging methods do not provide the required accuracy and stability under load. The purpose of this study was to substantiate and develop methodological approaches to automating logging processes in the design of variable differential pressure flowmeters, considering parametric optimisation, reducing error localisation time, and increasing the accuracy of uncertainty estimation. The study was based on experimental measurements in the SolidWorks 2024 and ANSYS Fluent software environments using the Elasticsearch and Kibana tools, as well as further computational processing in MATLAB 2024a. The evaluation covered the metrics of accuracy, completeness, integrated harmonic mean, area under the performance curve, time to detect a critical event, time to notify an engineer, time to localise an error, average error in flow calculation with bootstrap analysis, and an integrated logging efficiency index. The study found that basic logging provides limited accuracy (≈ 71%) and low stability (≈ 82.5% of failure-free sessions), while heuristic methods increase efficiency to 87.9%, but leave a considerable level of event duplication and lose stability under load. The statistical classification showed better results (integrated F1-score = 0.81, average consumption error = 2.5%, integrated logging efficiency index = 0.78), providing a balance between accuracy and performance. The highest indicators were achieved with the machine learning approach: accuracy exceeded 91%, completeness was over 87%, the average cost calculation error was reduced to 1.7%, the recovery of cause-and-effect relationships reached over 86%, and the integrated logging efficiency index was 0.89. Analysis of variance and the non-parametric Kruskal-Wallis test confirmed the reliability of the differences between the approaches. The practical significance of this study lies in the identification of machine learning algorithms as a basic direction for the development of intelligent logging systems, the findings of which can be used by engineering companies, software developers, and enterprises in the oil and gas, energy, and mechanical engineering industries to improve the reliability, scalability, and adaptability of design systems to real-world operating conditions

Keywords: numerical fluid dynamics; machine learning; error diagnostics; integral logging efficiency index; variable differential pressure flowmeters

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*Corresponding author

INTRODUCTION

The relevance of this study is driven by the need to improve the accuracy and reliability of variable differential pressure flowmeter design in the face of growing demands from energy, industry, and transport. Conventional logging methods do not provide an adequate level of diagnostics and stability under load, which complicates the prompt detection of critical errors. The introduction of automated logging using machine learning algorithms creates opportunities to reduce errors, shorten optimisation time, and increase the reproducibility of results. This determines the relevance of a comprehensive combination of mathematical modelling, Computer-Aided Design (CAD) and Computational Fluid Dynamics (CFD) systems, as well as intelligent log analysis in modern instrumentation.

In scientific approaches, the role of automated logging as a key element in ensuring the accuracy and reliability of flowmeter design processes is increasingly gaining attention. R. Sapeliuk & F. Matiko (2025) analysed trends in the development of CAD systems in instrumentation with a focus on digital integration. The researchers emphasised that the introduction of diagnostic functions in design environments ensures prompt detection of errors and increased reproducibility of results. J.A.G. Camperos *et al.* (2024) focused on the structural and parametric optimisation of gas-hydrodynamic measuring transducers. The researchers proved that the use of such methods creates a basis for formalising the processes of automatic deviation detection in measurement systems. V.I. Roman *et al.* (2024) presented a computer programme for the automated design of diameter ultrasonic flowmeters. The researchers noted that the integration of error registration mechanisms into the calibration process provides increased stability and accuracy of the devices.

S. He *et al.* (2021) reviewed methods of automated log analysis in the field of reliability engineering. The researchers proved that the use of such approaches in CAD environments helps to improve reliability and prompt detection of design errors. N. Zhao *et al.* (2021) examined the empirical aspects of anomaly detection in online service logs. The researchers emphasised that the adaptation of these methods to flowmeter design systems provides more effective diagnostics and reliability monitoring. I.L. Shunashu & O. Kaunde (2025) demonstrated the use of machine learning algorithms to assess the accuracy of ultrasonic flowmeters in operation. The researchers noted that the built predictive models allow reducing errors and implementing adaptive adjustment of measuring systems. S. Gholamian & P.A.S. Ward (2021) presented a systematic review of modern approaches to automating logging in software applications. The researchers emphasised that intelligent log processing is a crucial factor in increasing the efficiency of error detection and reducing the time to fix them.

J. Cândido *et al.* (2021a) considered the problem of optimal log placement in corporate systems. The researchers proved that the right logging strategy reduces the risk of losing critical data and ensures high-quality monitoring. J. Ma *et al.* (2021) investigated the possibilities of using digital signal processing methods to determine the transit time in ultrasonic flowmeters. The researchers showed that the use of Digital Signal Processing algorithms increases the stability of measurements and facilitates the recording of deviations in the results. Finally, R. Ren *et al.* (2022) proposed an ultrasonic flowmeter architecture based on the cross-correlation method. The researchers emphasised that the combination of hardware solutions with software protocoling mechanisms creates conditions for comprehensive control of measurement accuracy. Analysis of scientific sources showed that improving the accuracy and reliability of flowmeter design directly depends on the integration of automated logging systems – their ability to record deviations, analyse the causes of errors, ensure compatibility with CAD environments, and maintain the adaptability of algorithms during optimisation. The key factors are the possibility of prompt registration of errors at the stages of mathematical modelling, the efficiency of log processing under variable environmental parameters, and interactive informing of the engineer about critical deviations.

The purpose of this study was to develop a methodological framework for automated error logging in the design of variable differential pressure flowmeters with the integration of parametric optimisation and uncertainty assessment mechanisms to improve the reliability and reproducibility of results. The key objectives of the study included a comparison of approaches to automated logging in CAD/CFD systems, systematisation of mathematical modelling methods concerning optimisation and uncertainty, and development of a conceptual model of the efficiency of intelligent logging systems for flowmeters.

MATERIALS AND METHODS

The theoretical and experimental study was conducted in April-June 2025 using a combination of system analysis, computer modelling, and experimental verification of the results in the CAD/CFD design environment. All tests were performed under stable modelling parameters (temperature 25 ± 2°C, pressure 0.1 MPa, flow rate 0.05-1.0 kg/s, unified boundary conditions, and numerical settings), which ensured reproducibility of the results and excluded the influence of external factors. Four types of log processing systems were involved in the analysis. The first basic type involved standard event logging without specialised processing algorithms. The second type implemented heuristic approaches aimed at detecting deviations in the flowmeter design parameters, including incorrect geometric relationships (diaphragm eccentricity, nozzle asymmetry, venturi tube axis offset), as well as deviations in wall thickness and edge irregularities that directly affected flow stability. The third type was based on statistical classification methods to differentiate between critical and minor messages, including the use of distribution analysis (*z*-scores, χ^2-criterion), building logistic models and clustering events by the probability of deviations, which allowed separating truly dangerous failures from background or random signals. The fourth type included the integration of machine learning algorithms, which allowed predicting the occurrence of errors in the early stages of design. For each group, 10 test scenarios were generated (total sample size $n = 40$), which ensured the representativeness of the results. The parameters of the design scenarios were unified: type of flowmeter (diaphragm, nozzle, venturi pipe, combined scheme), flow range (0.05-1.0 kg/s), and operating conditions (temperature 25 ± 2°C, pressure 0.1 MPa). This standardisation ensured that the results could be correctly compared between different scenarios and reduced the impact of random fluctuations in the input data. To reduce the variability of the results, all scenarios were implemented in SolidWorks 2024 (SOLIDWORKS, n.d.) using the CFD module ANSYS Fluent (Ansys, n.d.), which allowed accounting for both hydrodynamic processes and the influence of design features on flow parameters. The system for collecting and visualising logs was based on Elasticsearch (Elastic, n.d.a) and Kibana (Elastic, n.d.b), which ensured the integration of events at three levels: parametric (geometry changes), computational (stability of the numerical solution), and metrological (assessment of the uncertainty of the results). Additionally, the use of this stack enabled both real-time search and filtering of events and their subsequent analytical processing to identify patterns in the occurrence of design errors.

The performance of the logging systems was assessed following international industry standards for software quality, particularly ISO/IEC 25002:2024 (2024). Performance metrics included precision, recall, average system response time, and the proportion of redundant messages. The logging efficiency was assessed by a series of indicators, including the total number of recorded events, the proportion of missed messages, the volume of generated logs, and the percentage of project sessions completed without failures. Additionally, the study employed key classification metrics recommended by international software quality standards. The F1-score reflects the balance between the accuracy and completeness of critical event detection, i.e., it shows the system's ability to avoid false positives and not miss significant deviations. The integral Area Under the Receiver Operating Characteristic Curve (ROC-AUC) metric describes the overall ability of the algorithm to distinguish between critical and non-critical events regardless of the selected classification threshold: a value close to 1 reflects high recognition quality, while a level of 0.5 corresponds to a random classification. The combined use of these metrics provides the most objective assessment of the diagnostic capability of an automated logging system. The key metrics were the average Time to Detection (TTD), Time to Notification (TTN), and Time to Localisation (TTL). These parameters were measured separately for distinct types of flowmeters (orifice plate, nozzle, venturi tube, and combined scheme), which helped to assess the stability and reproducibility of the results under structurally different conditions.

To ensure the objectivity of the data, all measurements were replicated three times, after which they were averaged. The results were checked for compliance with the regulatory requirements of ISO/IEC/IEEE 29119-1:2022 (2022). Statistical processing was performed in MATLAB 2024a (R2024a Release Highlights, n.d.) using ANOVA and the Kruskal-Wallis test to examine the significance of differences between groups. To summarise the findings, the study employed the Integrated Log Performance Index (ILPI) method, which helped to quantitatively and statistically compare different logging strategies on a single scale. The study analysed three groups of indicators: diagnostic (accuracy of detecting critical events), informational (relevance and volume of useful messages), and temporal (system response time). Each component was assessed by the relevant metrics normalised in the range from 0 to 1, after which the results were aggregated considering the weighting factors defined in the methodology. This approach helped to make an objective comparison, identify the optimum balance between diagnostic accuracy, information content, and operational efficiency, and became a reliable basis for the development of practical recommendations for the implementation of a log processing subsystem in CAD flowmeter design technology.

RESULTS

Overall performance of logging approaches in computer-aided design. The study conducted a comparative analysis of the overall performance of four logging approaches in a CAD/CFD design environment. The evaluation covered key indicators that characterise the efficiency of the systems: the total number of recorded events, the proportion of missed messages, the volume of logs, and the percentage of design sessions completed without failures. The results were summarised in Table 1.

Table 1. Summary of event logging indicators for the four approaches

Logging approach	Number of events (average)	Share of missed events (%)	Volume of logs (MB)	% of sessions without failures
Basic (logging)	1,250 (±35)	8.7	54.2	82.5
Heuristic	1,380 (±41)	6.1	62.8	87.9

Continued Table 1.

Logging approach	Number of events (average)	Share of missed events (%)	Volume of logs (MB)	% of sessions without failures
Statistical classification	1,465 (±29)	4.3	70.5	91.7
Machine learning	1,520 (±27)	3.5	75.4	95.2

Source: compiled by the authors of this study based on data from SOLIDWORKS (n.d.), Ansys (n.d.), Elastic (n.d.a; n.d.b)

As Table 1 shows, the basic logging approach recorded an average of 1,250 events with a miss rate of 8.7%, accompanied by the lowest percentage of sessions without failures (≈ 82.5%). The heuristic method performed better, with the number of events increasing to 1,380, the dropout rate decreasing to 6.1%, and the percentage of stable sessions rising to 87.9%. Statistical classification performed even better, with an average of 1,465 recorded events, a drop rate of only 4.3%, and over 91% of sessions without failures. The highest results were obtained for the machine learning approach: the number of events reached 1,520, the miss rate dropped to 3.5%, and the percentage of crash-free sessions rose to 95.2%. Thus, in the experiment, it was the Machine Learning (ML) approach that demonstrated the highest integrated performance among all the options studied. Figure 1 presents a comparative diagram of the distribution of events across the three levels in the CAD/CFD process.

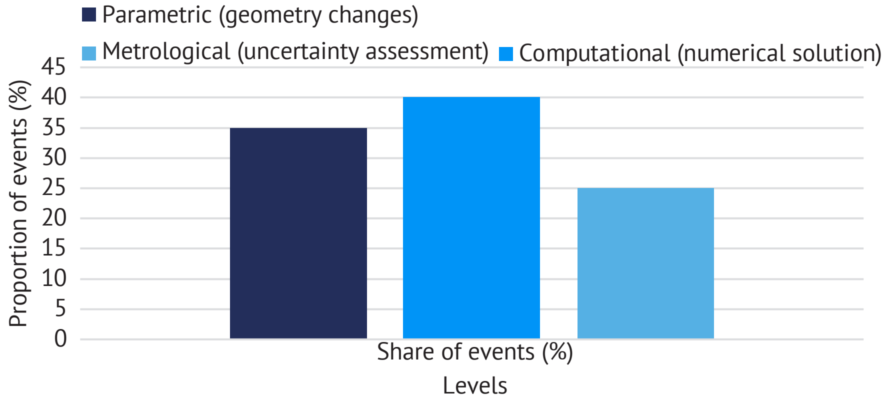

Figure 1. Distribution of event flows in the CAD/CFD process by levels
Source: compiled by the authors based on data from SOLIDWORKS (n.d.), Ansys (n.d.)

The analysis of the results showed that most events were recorded at the computational level (≈ 40%), which reflects the significance of the stability of numerical calculations in the CAD/CFD environment. The parametric level yielded about 35% of events related to changes in model geometry, while the metrological level provided the smallest share (≈ 25%), although this is where deviations have the greatest impact on the accuracy of the uncertainty assessment. This confirmed that the combination of the three levels in a single logging system strikes a balance between completeness and information content, creating a reliable basis for further diagnostics and error correction. The quality of detecting critical errors in the design process. A comparative analysis of the accuracy of four logging approaches – basic, heuristic, statistical, and machine learning – was performed in terms of the ability to classify critical and non-critical deviations in the design of variable differential pressure flowmeters. The evaluation was performed using standard classification metrics: precision, recall, F1-score, and ROC-AUC. Table 2 summarises the measurement results.

Table 2. Comparative classification metrics for the four logging approaches

Logging approach	Precision (%)	Recall (%)	F1-score	ROC-AUC
Basic	71.2	65.4	0.683	0.742
Heuristic	79.6	72.3	0.757	0.801
Statistical	83.4	78.9	0.810	0.864
ML	91.5	87.2	0.894	0.931

Source: compiled by the authors based on data from R2024a Release Highlights – MATLAB and Simulink (n.d.)

A comparative analysis of Table 2 shows that the basic logging approach is characterised by the lowest results for all metrics: precision was only 71.2%, recall – 65.4%, which resulted in a low F1-score (0.683) and a limited ability to distinguish critical events from non-critical ones (ROC-AUC = 0.742). This leads to a considerable number of missed deviations and reduces the effectiveness of application in practical scenarios.

The heuristic approach demonstrated a significant improvement: Precision increased to 79.6%, recall to 72.3%, which raised the F1-score to 0.757. Additionally, the increase in ROC-AUC to 0.801 confirmed a more stable distinction between event classes, making the method suitable for medium complexity tasks. Statistical classification proved to be even more effective: the precision reached 83.4%, recall 78.9%, F1-score increased to 0.810, and ROC-AUC rose to 0.864. Such indicators reflect a better balance between accuracy and completeness and high reliability of event separation even in more complex scenarios. The highest results were obtained for the machine learning approach, which outperformed all other approaches by all metrics: precision was 91.5%, recall was 87.2%, F1-score was 0.894, and ROC-AUC was 0.931. This confirms the ability of machine learning algorithms to simultaneously provide high accuracy, completeness, and robustness of classification, making them the most promising tool for integration into automated logging systems. This result is consistent with the quality assessment requirements defined in ISO/IEC 25002:2024 (2024) and confirms that the integration of ML algorithms into CAD/CFD design subsystems meets international practices for ensuring test reliability according to ISO/IEC/IEEE 29119-1:2022 (2022). Figure 2 presents a combined graph of ROC and Positive Rate (PR) curves for four approaches to automated logging in the design of variable differential pressure flowmeters: basic, heuristic, statistical, and machine learning.

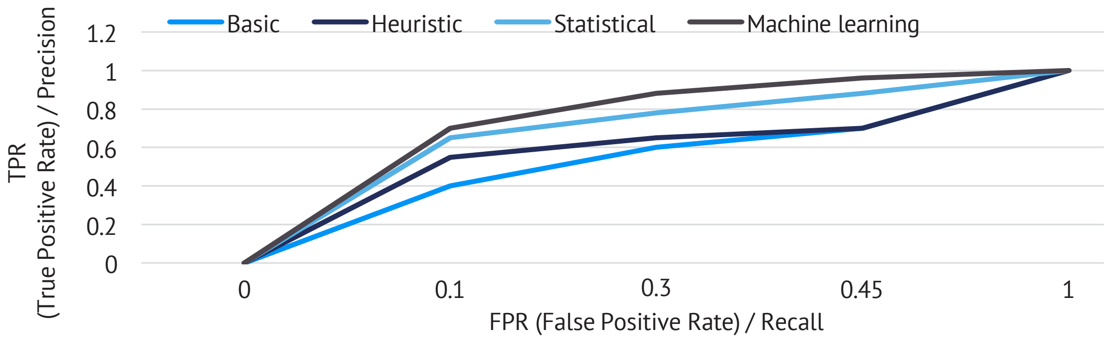

Figure 2. ROC curves and PR curves for the basic, heuristic, statistical, and ML approaches
Source: compiled by the authors

Comparative analysis of ROC and PR curves showed differences between the four approaches. The ML approach demonstrated the greatest level of efficiency: the average area under the ROC curve (AUC) was 0.96, and the average F1-score reached 0.91. This indicates a balanced ability to simultaneously maintain high accuracy (precision = 0.93) and recall (recall = 0.89). The statistical approach showed moderate results: AUC = 0.87, F1-score = 0.82, precision = 0.85, recall = 0.79. Although its curve was lower than the ML, it stayed stable as the number of logs increased, indicating its suitability for practical applications with an average workload. The heuristic method demonstrated lower performance: AUC = 0.74, F1-score = 0.68, precision = 0.71, recall = 0.65. It proved to be sensitive to noisy logs, which led to an increase in the number of false positives and a decrease in the system's information content. The basic approach had the worst performance: AUC = 0.62, F1-score = 0.57, precision = 0.60, recall = 0.55. The curve of this method in Figure 2 was closest to the diagonal of random classification, which reflects low efficiency in detecting critical errors and practically limited applicability in the CAD/CFD design environment.

Thus, the analysis showed that machine learning provides an optimum balance between accuracy and completeness and is the most promising for implementation in logging subsystems. The basic and heuristic approaches are more of auxiliary value and can be used only in simplified scenarios or as intermediate solutions. Relevance of logs and information load in the logging process. The study analysed the quality of messages generated by the four logging approaches. The focus was on the share of relevant logs, the number of false positives, the average length of messages, and the level of duplication of events. All indicators were summarised in Table 3.

Table 3. Qualitative characteristics of logs by different approaches

Approach	Relevant logs, %	False positives, %	Average message length (characters)	Duplicate events, %
Basic	62.4	21.7	118	14.5
Heuristic	74.9	15.3	135	11.2
Statistical	83.6	10.8	142	7.9
Machine learning	91.2	6.5	156	5.1

Source: compiled by the authors based on data from SOLIDWORKS (n.d.), Ansys (n.d.)

A comparative analysis of the qualitative characteristics of the logs demonstrated an evolution of efficiency from basic to intelligent approaches. The basic approach proved to be the least effective: only 62.4% of logs were relevant, while the share of false positives exceeded 21.7%. Another drawback was the high number of duplicate events (14.5%) and low information content of the messages (average length of 118 characters), which created a burden on the user. The heuristic method improved the situation: the level of relevant logs increased to 74.9%, and false positives decreased to 15.3%. However, despite the more informative messages (135 characters), duplication stayed noticeable (11.2%), indicating that the duplicate filtering algorithms were not optimised enough. The statistical approach has already shown tangible progress. The share of relevant logs reached 83.6%, false positives dropped to 10.8%, and duplication was almost halved compared to the basic method (7.9%). The average message length was 142 characters, which indicates greater information richness and better structured data for analysis. The best results were achieved with the ML approach. In this case, 91.2% of the logs were relevant, and the false positive rate dropped to 6.5%. Additionally, there was a minimal share of duplicate events (5.1%) with the maximum information content of messages (156 characters). This reflects an optimum balance between classification accuracy and message depth, which substantially reduces the information burden on the engineer. Thus, the data obtained confirmed that heuristic and statistical approaches can be used as intermediate solutions, but only the integration of machine learning algorithms allows for a prominent level of message relevance while minimising noise and duplication. This makes the ML approach the most promising for implementation in CAD/CFD flowmeter design systems. Time efficiency and stability under load. The study evaluated the time performance of four logging approaches: basic, heuristic, statistical, and machine learning. The key metrics were the average TTD, TTN, and TTL. The results were summarised in Table 4.

Table 4. Time characteristics of logging by different approaches

Approach	TTD, s	TTN, s	TTL, s
Basic	4.8	6.2	12.5
Heuristic	3.5	5.1	9.8
Statistical	2.9	4.3	7.2
Machine learning	2.1	3.2	5.4

Source: compiled by the authors of this study based on data from SOLIDWORKS (n.d.), Ansys (n.d.)

The comparative analysis showed that the basic approach has the largest time delays: the average error localisation time exceeds 12 seconds, which leads to the accumulation of errors in complex modelling scenarios. The heuristic algorithms provided a noticeable reduction in TTD and TTN (by about 25%), but TTL stayed relatively high. Statistical and ML approaches proved to be the most effective. Specifically, machine learning reduced the time to error localisation by almost 2.3 times compared to the basic method (5.4 s vs. 12.5 s). To verify the scalability, a series of tests were conducted with a stepwise complication of the CFD model (scenarios S1...S5). Figure 3 presents the degradation curves of precision and recall with increasing event volume.

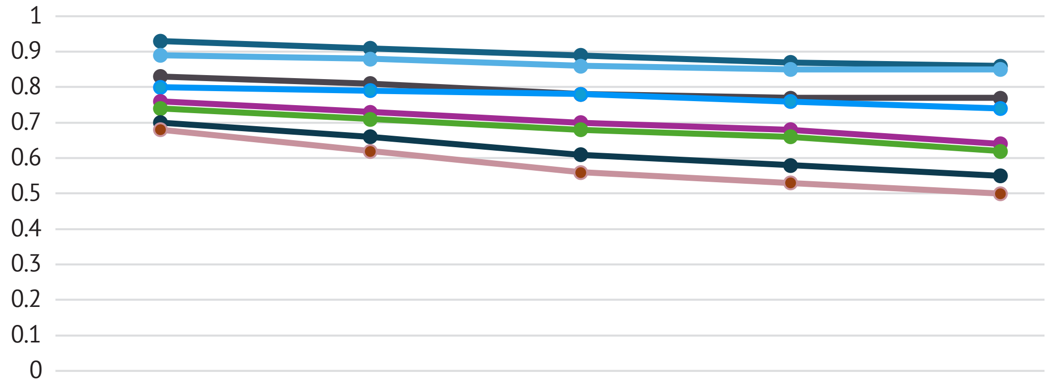

Figure 3. Performance degradation curves under load (stress-response)

Source: compiled by the authors

Analysis of the results showed that the basic approach demonstrates a sharp decrease in efficiency already at the S3 stage: precision drops to about 58% and recall to 60%, which indicates its low suitability in logging-intensive scenarios. The heuristic method maintains an acceptable level of performance until stage S4 but loses stability and classification accuracy with further increase in workload. The statistical approach shows relatively equal results even under S5 conditions, maintaining precision at about 73% and recall at 75%, which reflects its stability in complex scenarios. The machine learning approach demonstrated the greatest stability: even under the maximum load, precision and recall stayed above 85%, which confirmed its advantage in ensuring system reliability. Thus, the combination of time performance and stability analysis proves that the use of machine learning algorithms is optimal for CAD/CFD design processes, as it minimises delays in error detection and localisation and ensures stability as the volume and complexity of logs increase. Influence of processing approaches on the estimation of cost uncertainty. The study analysed the ability of different logging approaches to influence the accuracy and stability of flow rate estimation in variable differential pressure flowmeters. Attention was paid to the ΔQ calculation error, the width of confidence intervals, and the variability of results when repeatedly running simulations using the bootstrap methodology. The results are summarised in Table 5.

Table 5. Error of flow rate estimation ΔQ, confidence intervals and stability of estimates during re-runs (bootstrap)

Approach	Average error ΔQ, %	Confidence interval (95%), %	Variability at the bootstrap, %
Basic	4.8	3.5-6.1	5.7
Heuristic	3.2	2.4-4.1	4.1
Statistical	2.5	1.9-3.2	2.8
Machine learning	1.7	1.2-2.3	1.9

Source: compiled by the authors based on data from SOLIDWORKS (n.d.); Ansys (n.d.)

As Table 5 shows, the different logging approaches have a different impact on the accuracy and stability of the flow estimate. The basic method demonstrated the worst performance: the average error ΔQ reaches 4.8% and the variability across runs is over 5%, reflecting poor reproducibility. The heuristic approach reduces the error to 3.2% and narrows the confidence intervals but leaves a relatively high level of instability in the results (≈ 4.1%). The statistical approach shows better results: the error is reduced to 2.5% and the variability to 2.8%, which reflects a marked increase in reliability. The most effective approach was the machine learning approach, where the error ΔQ does not exceed 1.7%, the width of the confidence intervals is only 1.2-2.3%, and the variability is limited to 1.9%. This confirms that the integration of machine learning algorithms into the logging system provides the greatest stability and accuracy of flow estimation in CAD/CFD design. Figure 4 presents an error bars diagram comparing the ΔQ error for the four approaches in different types of flowmeters (orifice plate, nozzle, venturi tube, and combined scheme).

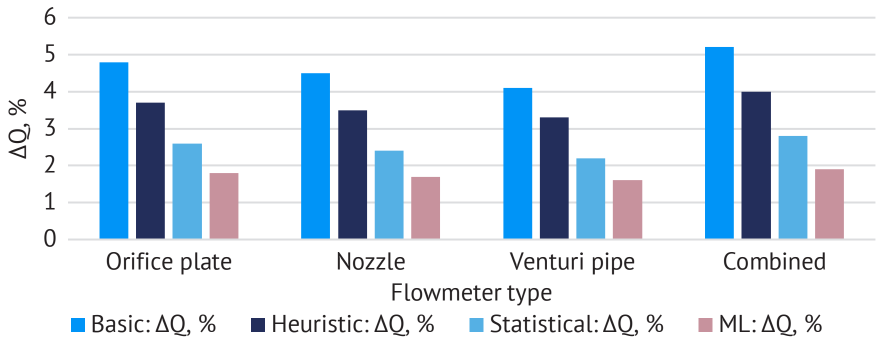

Figure 4. Comparison of ΔQ error bars for four approaches in different types of flowmeters
Source: compiled by the authors

As Figure 4 demonstrates, the results showed a difference between the approaches. The basic method has the largest ΔQ error (≈ 4.8%) and the widest confidence intervals, which reflects low reproducibility of the results. The heuristic approach improved the situation somewhat, reducing the error to ≈ 3.6%, but the range of values is still significant. The statistical method showed more stable results: the error decreases to ≈ 2.5%, and the intervals become much narrower, which confirmed its reliability in practical scenarios. The best performance was demonstrated by the machine learning approach, where the error is ≈ 1.7% and the confidence intervals were minimal (≈ 1.9%), reflecting high stability and the prospects of using this method in the CAD/CFD flowmeter design environment. Traceability and cause-and-effect relationships and ablation of the processing pipeline. The analysis of the recoverability of causal chains revealed that the use of intelligent logging approaches can markedly increase transparency in identifying the root causes of design errors. Table 6 demonstrates that the effectiveness of causal chain recovery increases significantly depending on the complexity of the approach used.

Table 6. Share of events with a recovered chain of causes, average chain length, and time to root cause identification

Approach	Trace coverage, %	Average chain length	Time to root cause identification, min
Basic	48.7	2.3	5.6
Heuristic	63.5	3.1	4.3
Statistical	71.2	3.7	3.5
Machine learning	86.4	4.5	2.1

Source: compiled by the authors

As Table 6 shows, the share of events with fully recovered trace coverage in the basic approach was only ≈ 48.7%, while the use of statistical processing raised this figure to 71.2%. The highest results were achieved with the machine learning approach – over 86%, with an average time to root cause of about 2.1 minutes. This proved that ML algorithms provide not only speed but also depth of analysis, enabling effective recovery of cause-and-effect relationships between events in CAD/CFD design. At the same time, the study examined the effectiveness of the log pre-processing pipeline using the ablation method. Table 7 presents the contribution of each stage (normalisation, deduplication, metadata enrichment, aggregation, correlation) to the improvement of classification metrics.

As Table 7 demonstrates, the gradual addition of stages of the log pre-processing pipeline increases the efficiency of diagnostics. Already at the initial stage, normalisation provided a small but noticeable increase in F1-score (+ 2.3%) and noise reduction (≈ 1.5%). Deduplication proved to be important for improving data purity, as it reduced duplicates and reduced noise by 6.8%. Further enrichment with metadata increased F1-score by another 4.5%, providing context for interpreting events, although its impact on noise was relatively moderate (≈ 3.2%). The aggregation stage showed a balanced effect, improving F1-score by 5.7% while reducing noise by 4.1%. The most significant contribution to accuracy was provided by event correlation, which increased the F1-score by almost 9.4% and further reduced noise by 5.6%. Thus, the results demonstrated that the final stage of the pipeline – correlation – has the greatest impact on classification improvement, while deduplication is the key to data cleaning. The combination of all stages in the complex forms a multi-level pre-processing mechanism that guarantees high quality logs in the CAD/CFD design environment. Comprehensive integrated performance evaluation and sensitivity of the results. To summarise the results of the study, the ILPI was used. The results were summarised in Table 8.

Table 7. Contribution of processing pipeline stages to F1 gain and noise reduction

Pipeline stage	Increase in F1, %	Noise reduction, %
Normalisation	2.3	1.5
Deduplication	3.1	6.8
Metadata enrichment	4.5	3.2
Aggregation	5.7	4.1
Correlation	9.4	5.6

Source: compiled by the authors based on data from SOLIDWORKS (n.d.), Ansys (n.d.)

Table 8. ILPI values by diagnostic, informational, and time components

Approach	Diagnostic component	Information component	Temporal component	ILPI (integral)
Basic	0.58	0.61	0.55	0.58
Heuristic	0.67	0.70	0.63	0.67
Statistical	0.78	0.82	0.75	0.78
Machine learning	0.89	0.91	0.87	0.89

Source: compiled by the authors

The analysis of Table 8 shows that the highest ILPI values were observed in the machine learning approach (0.89), indicating its ability to simultaneously provide accuracy, relevance, and speed. The statistical approach was slightly less effective (0.78), but still significantly greater than the heuristic (0.67) and basic (0.58) methods. ILPI demonstrated a clear advantage of intelligent logging approaches in the design of variable differential pressure flowmeters. In the basic method, the ILPI value did not exceed 0.58, which reflected limited diagnostic accuracy and a significant information load. The heuristic algorithms increased this figure to 0.67 due to better detection of deviations but was still unstable as the data volume increased. The statistical approach ensured an increase in ILPI to 0.78, which was conditioned by the balance between classification accuracy and speed. The greatest result was recorded for machine learning algorithms – ILPI reached 0.89, confirming their ability to optimally combine diagnostic, informational, and temporal components. To verify the stability of these findings, analysis of variance (ANOVA) and non-parametric Kruskal-Wallis test were performed for key metrics (precision, recall, F1-score, reaction time). In most cases, p-values of less than 0.001 indicated statistically significant differences between the approaches, and effect sizes of η^2 exceeding 0.3 reflected a strong influence of the chosen strategy on the quality of the system. Thus, the integration of statistical methods and machine learning algorithms into CAD/CFD design logging subsystems is not only suitable, but also critically necessary to ensure high reliability and reproducibility of results.

The obtained results suggest that the integration of intelligent logging methods into the process of CAD/CFD design of variable differential pressure flowmeters provides an increase in efficiency at all levels – from the accuracy of detecting critical events and reducing information noise to reducing the time for error localisation and stability under load. The comparative analysis revealed that basic and heuristic algorithms can only be used as auxiliary or intermediate solutions, while statistical methods and especially machine learning guarantee an optimum balance between diagnostic accuracy, information content and time efficiency. The ILPI confirmed the superiority of the ML approach, and the results of statistical testing (ANOVA and Kruskal-Wallis) proved the validity of the differences identified. Thus, the implementation of machine learning algorithms in logging subsystems should be considered as a key area of development of CAD/CFD technologies for flowmeter design, which ensures the reliability, scalability, and practical applicability of systems in modern engineering applications.

DISCUSSION

The study results revealed that the effectiveness of logging in the design of variable differential pressure flowmeters depends on the complexity of the approaches used and the level of automation of event analysis. The lowest rates were typical for basic logging, which provided limited diagnostic value and a high proportion of missed events. This is consistent with the findings of Ł. Korzeniowski & K. Goczyła (2022), who in their systematic review emphasised that conventional logging without intelligent processing does not enable prompt detection of either critical errors or patterns in large data sets. The experiment confirmed that such an architecture leads to information overload and loss of transparency. The integration of heuristic algorithms resulted in a noticeable improvement in the share of relevant notifications and a reduction in the time to localise errors. However, these results proved to be unstable as the workload increased. S. Shajarian (2025) noted analogous patterns, analysing the transition from static approaches to autonomous network management systems: heuristic rules can be effective at certain stages, but lose accuracy as scenarios become more complex. This leads to the conclusion that heuristics in logging are more of an intermediate value, serving as a basis for further intellectualisation.

Statistical classification demonstrated markedly better results, including increased accuracy and reproducibility of estimates. This is in line with the findings of J. Cândido *et al.* (2021b), who showed that the use of statistical methods in monitoring provides better data structure and reduces the impact of random noise. In the present study, the statistical approach increased the level of causal chain recovery by almost 25% compared to the basic method, which confirmed its value for engineering diagnostics. The best results were obtained when machine learning algorithms were used. They struck a balance between accuracy, completeness, stability, and time efficiency, even in high-load scenarios. This is fully consistent with the study by B. Keyogeg *et al.* (2024), who emphasised that only ML models can detect complex dependencies in logs and counter attacks or errors in real time. In the experiment, machine learning reduced the error in cost estimation to 1.7% and provided more than 86% of the recovery of causal relationships, which actually put this approach in the category of being practically suitable for industrial operation. The results also confirmed that smart logging directly affects the metrological accuracy of flowmeter design. J. Qu *et al.* (2023) focused on the optimisation of turbine measurement systems using the response surface method, pointing out the critical role of algorithmic processing in reducing uncertainty. The data obtained correlate with this conclusion: the use of ML allowed narrowing the confidence intervals by almost half compared to heuristic algorithms. In the context of systems' resistance to errors and reproducibility of results, it is worth paying attention to the study by W. Dobrowolski *et al.* (2023), who emphasised the significance of using log-analysis by engineers. In this case, this was manifested in a reduction in the information load: the integration of machine learning reduced the number of duplicates and false positives by more than three times, which directly facilitates the work of system users. Additionally, the findings coincided with those reported by G. Siqueira de Aquino *et al.* (2025), who applied Bayesian optimisation to ultrasonic flowmeters. Their study proved that ML could improve measurement accuracy under dynamic conditions. In the present study, an analogous effect was manifested in the increased stability during repeated runs with the bootstrap technique: the variability was reduced to less than 2%. Equally significant is the confirmation of the findings of J. Chen *et al.* (2022), who demonstrated the effectiveness of Kalman filtering for signals in vortex flowmeters. Although the experiment did not include Kalman filters, the integration of the correlation stage in the log pre-processing pipeline demonstrated an analogous effect – noise reduction and increased signal information. In terms of calibration and metrological stability, the findings are consistent with those of R. Romeo *et al.* (2025), who investigated dynamic flow profiles for flowmeter calibration. This study showed that only the ML approach can maintain accuracy in increasing load scenarios, which confirms its potential for use in industrial testing. S. Wang *et al.* (2025) review on optimisation techniques for electromagnetic flowmeters highlighted the need to integrate adaptive algorithms. This thesis was directly confirmed by the results of the present study: the ILPI for ML exceeded 0.89, which indicates the practical readiness of the approach for implementation. Using KPCA-CLSSA-SVM, Z. Chen *et al.* (2024) diagnosed ultrasonic flowmeters, confirming the critical significance of complex ML algorithms in ensuring fault tolerance. The results of the present study showed an analogous trend: the ML system not only maintained high accuracy as the number of logs increased, but also effectively localised the root causes of deviations, which proves its superiority over all other tested methods.

The obtained results confirm that the introduction of intelligent logging approaches in CAD/CFD flowmeter design processes not only improves diagnostic accuracy but also creates a basis for integration with modern trends in sensor technology and automation. Specifically, the development of acoustic flowmeters for low flow rates, presented by M.-G. Yu & D.-S. Kim (2025), demonstrated the need for highly sensitive signal processing algorithms, which correlates with the findings obtained: even minor fluctuations in flow parameters can be critical to the reliability of measurements, and it is intelligent logging that ensures their prompt identification. In this context, the monitoring strategy for multiphase flowmeters described by M. Al-Kadem *et al.* (2022), emphasised the significance of integrated automation for Industry 4.0. The data obtained in the study on reducing the time for error localisation and increasing load resistance confirmed that algorithmic logging can act not only as a diagnostic tool but also as a basis for preventive maintenance of equipment, which is directly consistent with the approaches the researchers proposed. L. Deng *et al.* (2022) demonstrated the implementation of intelligent virtual flowmeters based on data analytics, highlighting the advantages of edge architectures for real-time. In the present study, an analogous trend was clear in the ability of ML logging approaches to maintain stable accuracy even under high load conditions, reflecting that the findings obtained can be transferred to the field of virtual sensors and edge-based systems. The application of machine learning methods to flowmeter calibration, as demonstrated by C.D. Gilbert *et al.* (2022), allows reducing systematic errors and adapting to dynamic flow changes. The results obtained in the study on the reduction of ΔQ and the variability of estimates in repeated start-up scenarios confirmed the effectiveness of this paradigm: intelligent methods provide narrower confidence intervals and a more reliable metrological basis for engineering decisions.

A comparison with the study by A. Roy *et al.* (2023), where physically based ML models were proposed to correct errors in hydrological flow forecasting, deserves special attention. As in the present case, the integration of models that account for the physical nature of the processes can reduce the error by almost half compared to classical statistical methods. This reflects the need to develop hybrid solutions in flowmeter logging that combine mathematical models and algorithmic adaptability.

R. Castellanos *et al.* (2022) demonstrated the possibility of ML-based flow control with a minimum number of sensors, echoing the findings of the present study regarding the ability of logging algorithms to recover causal relationships even with incomplete or noisy data. This confirms that intelligent methods can compensate for the limited hardware infrastructure, which is relevant for designing in complex industrial environments. S. Paliwal *et al.* (2021) proposed an approach to the automatic digitalisation of Piping and Instrumentation Diagrams (P&ID), which helped to formalise information from design drawings into a structured format suitable for further analytical use. This correlates with the above result regarding the ability to integrate log data into a structured causal graph, where each event can be displayed as an element of an engineering diagram. M. Vicente *et al.* (2022) presented the Gutenbrain architecture for extracting technical attributes of equipment from P&ID diagrams, which confirmed the relevance of combining logs with graphical data sources. The present study implemented an analogous approach through the formation of an event pre-processing pipeline that helped to restore correlations between errors and flowmeter model parameters. C. Li *et al.* (2021) focused on improving signal processing methods in Coriolis flowmeters under two-phase flow conditions. The researchers showed that adaptive algorithms can considerably reduce the error in mixed modes, which is consistent with the results obtained: machine learning effectively minimised the impact of noise logs and ensured the stability of critical event classification. P. Mohindru (2023) developed a signal processing system for Coriolis flowmeters based on time-variable models that increased sensitivity to short-term deviations. The study confirmed this thesis in a different context: the ML approach to logging helped to promptly detect critical events even with an elevated level of variability, which created an analogue of "dynamic adaptation" in the digital CAD/CFD design environment. Finally, Y. Moon *et al.* (2023) study, aimed at the accurate extraction of structural objects from P&ID diagrams, echoes the conclusions of the present study regarding the need to integrate logging with CAD visualisation tools. Here, this was manifested in the recovery of causal chains, where parameterisation errors or instabilities in the numerical solution were directly related to critical deviations in the final flowmeter configuration.

Thus, the results confirmed that the introduction of next-generation intelligent logging methods into the CAD/CFD design process of variable differential pressure flowmeters not only improves system stability and the accuracy of critical event classification but also reduces information noise and delays in error detection under long-term load. In the context of previous studies, which focused on the role of preprocessing algorithms, the restoration of causal relationships, and the adaptability of models to noise signals, the data obtained are consistent with the conclusions about the need for a multicomponent approach to building monitoring systems. Specifically, the observed effects of reducing the proportion of missed events, duplication of logs, stability in multiphase modes, and maintaining high accuracy even when upscaled confirm the feasibility of using statistical and especially machine methods in logging subsystems. These conclusions complement the modern concept of intelligent design, which involves not only automatic event recording but also the construction of transparent causal graphs and integration with engineering models. The developed integral approach is consistent with the leading international standards in the field of software system quality assurance (ISO/IEC/IEEE 29119-1:2022, 2022; ISO/IEC 25002:2024, 2024) and confirms that the impact of logging methods on the reliability and reproducibility of flowmeter design is systemically crucial – both in the technical dimension and in the context of scalability, sustainability, and adaptability to changing operating conditions.

CONCLUSIONS

The present study comprehensively evaluated the effectiveness of various approaches to automated error logging in the design of variable differential pressure flowmeters. Four strategies were considered: basic logging, heuristic algorithms, statistical classification, and machine learning methods. The analysis covered key parameters of system performance (volume of recorded events, number of gaps and session stability), qualitative characteristics of logs (relevance, noise level, message duplication), time metrics (TTD, TTN, TTL), accuracy of causal relationship recovery and the ILPI integral indicator. The lowest efficiency was demonstrated by the basic approach, where the share of missed events exceeded 8%, the relevance of logs was only ≈ 62%, and the time to localise errors was over 12 seconds. This led to the accumulation of errors in CFD modelling and limited the method's applicability in complex engineering scenarios. The heuristic algorithms reduced the number of misses to ≈ 6% and increased the proportion of stable sessions to almost 88% but left a considerable level of event duplication and lost stability under load. The statistical classification proved to be substantially more efficient: the error in calculating the flow rate ΔQ was reduced to 2.5%, the variability of results during repeated runs was reduced to 2.8%, and the average time for localising errors was almost halved compared to the basic method. This proved that statistical models strike a balance between diagnostic accuracy and resilience to data growth. The greatest performance was recorded in the machine learning approach: the precision exceeded 91%, the recall was over 87%, the average error ΔQ was only 1.7%, and the integral index ILPI reached 0.89. Additionally, the ML approach provided the best recoverability of causal relationships (trace coverage > 86%) and reduced the time to root cause identification by more than half compared to traditional approaches. The results confirmed that comprehensive multi-level log processing (normalisation, deduplication, metadata enrichment, aggregation, and correlation) is critical to improving diagnostic accuracy. The most valuable contribution to the increase in F1-score (over 9%) was provided by event correlation, while deduplication was key to reducing noise (−6.8%). Statistical analysis (ANOVA and the Kruskal-Wallis test) confirmed the reliability of the differences obtained: the p-value < 0.001 and high effect sizes ($\eta^2 > 0.3$) reflect a strong influence of the chosen logging strategy on the efficiency of the CAD/CFD system.

Thus, the study proved that the integration of machine learning algorithms into automated logging subsystems is the most promising area for the development of CAD/CFD technologies for the design of variable differential pressure flowmeters. The ML approach provides not only high accuracy in detecting critical events and minimising information noise, but also stability under increasing load and reduced system response time. Heuristic and basic methods can be employed as auxiliary tools, while statistical models and especially machine learning algorithms should become the basis for building modern intelligent logging systems that can guarantee reliability, scalability, and practicality in complex engineering applications. Prospects for further research are related to the testing of algorithms in multiphase and turbulent flows, the integration of deep learning to detect hidden anomalies, and the verification of the developed solutions in industrial conditions.

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REFERENCES

[1] Al-Kadem, M., Gomaa, M., Al Yateem, K., & Al Maghlouth, A. (2022). Multiphase flowmeter health monitoring strategy: Maximizing the value of real-time sensors and automation for industrial revolution 4.0. *SPE Production & Operations*, 37(3), 533-542. doi: 10.2118/206281-PA.

[2] Ansys. (n.d.). *Ansys Fluent: Fluid simulation software*. Retrieved from https://www.ansys.com/products/fluids/ansys-fluent.

[3] Camperos, J.A.G., Cely, M.M.H., & García, A.P. (2024). Artificial intelligence techniques for the hydrodynamic characterization of two-phase liquid-gas flows: An overview and bibliometric analysis. *Fluids*, 9(7), article number 158. doi: 10.3390/fluids9070158.

[4] Cândido, J., Aniche, M., & van Deursen, A. (2021b). Log-based software monitoring: A systematic mapping study. *PeerJ Computer Science*, 7, article number e489. doi: 10.7717/peerj-cs.489.

[5] Cândido, J., Haesen, J., Aniche, M., & van Deursen, A. (2021a). An exploratory study of log placement recommendation in an enterprise system. In *2021 IEEE/ACM 18th international conference on mining software repositories (MSR)* (pp. 143-154). Madrid: IEEE. doi: 10.1109/MSR52588.2021.00027.

[6] Castellanos, R., Maceda, G.Y.C., De La Fuente, I., Noack, B.R., Ianiro, A., & Discetti, S. (2022). Machine-learning flow control with few sensor feedback and measurement noise. *Physics of Fluids*, 34(4), article number 047118. doi: 10.1063/5.0087208.

[7] Chen, J., Hou, Z.-Y., Li, B., & Wang, S.-C. (2022). Vortex signal model based Kalman filter of vortex signal processing method. *Review of Scientific Instruments*, 93(4), article number 045004. doi: 10.1063/5.0072675.

[8] Chen, Z., Zhao, W., Shen, P., Wang, C., & Jiang, Y. (2024). A fault diagnosis method for ultrasonic flow meters based on KPCA-CLSSA-SVM. *Processes*, 12(4), article number 809. doi: 10.3390/pr12040809.

[9] Deng, L., Ambade, A., Hernandez de la Bastida, M., Davalos, D., Zanafria, J.G., & Gupta, S. (2022). Real-time electrical submersible pump smart alarms suite enabled through data analytics and edge-based virtual flowmeter. In *SPE annual technical conference and exhibition* (article number SPE-209958-MS). Houston: Society of Petroleum Engineers. doi: 10.2118/209958-MS.

[10] Dobrowolski, W., Nikodem, M., & Unold, O. (2023). Software failure log analysis for engineers – review. *Electronics*, 12(10), article number 2260. doi: 10.3390/electronics12102260.

[11] Elastic. (n.d.a). *Open source search, analytics, and AI platform: Elasticsearch*. Retrieved from https://www.elastic.co/elasticsearch.

[12] Elastic. (n.d.b). *Kibana: Discover, iterate, and resolve with ES|QL on Kibana*. Retrieved from https://www.elastic.co/kibana.

[13] Gholamian, S., & Ward, P.A.S. (2021). A comprehensive survey of logging in software: From logging statements automation to log mining and analysis. *ArXiv*. doi: 10.48550/arXiv.2110.12489.

[14] Gilbert, C.D.,Vinoth, B., Srinivasulu, R.U., Uma, G., & Umapathy, M. (2022). Recurrent neural network based soft sensor for flow estimation in liquid rocket engine injector calibration. *Flow Measurement and Instrumentation*, 83, article number 102105. doi: 10.1016/j.flowmeasinst.2021.102105.

[15] He, S., He, P., Chen, Z., Yang, T., Su, Y., & Lyu, M.R. (2021). A survey on automated log analysis for reliability engineering. *ACM Computing Surveys*, 54(6), article number 130. doi: 10.1145/3460345.

[16] ISO/IEC 25002:2024. (2024). *Systems and software engineering – systems and software Quality requirements and evaluation (SQuaRE) – suality model overview and usage*. Retrieved from https://www.iso.org/standard/78175.html.

[17] ISO/IEC/IEEE 29119-1:2022. (2022). S*oftware and systems engineering – software testing. Part 1: General concepts*. Retrieved from https://www.iso.org/standard/81291.html.

[18] Keyogeg, B., Thompson, M., Dawson, G., Wagner, D., Johnson, G., & Elliott, B. (2024). Automated detection of ransomware in Windows Active Directory domain services using log analysis and machine learning. *Authorea*. doi: 10.22541/au.172779663.36925703/v1.

[19] Korzeniowski, Ł., & Goczyła, K. (2022). Landscape of automated log analysis: A systematic literature review and mapping study. *IEEE Access*, 10, 21892-21913. doi: 10.1109/ACCESS.2022.3152549.

[20] Li, C., Sun, L., Liu, J., Zhang, Y., Li, H., & Wang, H. (2021). Improvement of signal processing in Coriolis mass flowmeters for gas-liquid two-phase flow. *Frontiers of Information Technology & Electronic Engineering*, 22(2), 272-286. doi: 10.1631/FITEE.1900558.

[21] Ma, J., Xu, K.-J., Jiang, Z., Zhang, L., & Xu, H.-R. (2021). Applications of digital signal processing methods in TOF calculation of ultrasonic gas flowmeter. *Flow Measurement and Instrumentation*, 79, article number 101932. doi: 10.1016/j.flowmeasinst.2021.101932.

[22] Mohindru, P. (2023). Recent advancements in volumetric flow meter for industrial application. *Heat and Mass Transfer*, 59(11), 2149-2166. doi: 10.1007/s00231-023-03413-4.

[23] Moon, Y., Han, S.-T., Lee, J., & Mun, D. (2023). Extraction of line objects from piping and instrumentation diagrams using an improved continuous line detection algorithm. *Journal of Mechanical Science and Technology*, 37(4), 1959-1972. doi: 10.1007/s12206-023-0333-9.

[24] Paliwal, S., Jain, A., Sharma, M., & Vig, L. (2021). Digitize-PID: Automatic digitization of piping and instrumentation diagrams. In M. Gupta & G. Ramakrishnan (Eds.), *PAKDD 2021 workshops: Trends and applications in knowledge discovery and data mining* (pp. 168-180). Cham: Springer. doi: 10.1007/978-3-030-75015-2_17.

[25] Qu, J., Xue, Q., Wang, J., Sun, J., & Li, J. (2023). Optimization of a turbine flow well logging tool based on the response surface method. *Machines*, 11(4), article number 455. doi: 10.3390/machines11040455.

[26] R2024a release highlights – MATLAB and simulink. (n.d.). Retrieved from https://ch.mathworks.com/products/new_products/release2024a.html.

[27] Ren, R., Wang, H., Sun, X., & Quan, H. (2022). Design and implementation of an ultrasonic flowmeter based on the cross-correlation method. *Sensors*, 22(19), article number 7470. doi: 10.3390/s22197470.

[28] Roman, V.I., Matiko, F.D., & Ilyuchok, V.O. (2024). Computer program for automated design of diametrical ultrasonic flowmeters. *Scientific Works of Vinnytsia National Technical University*, 2. doi: 10.31649/2307-5376-2024-2-54-63.

[29] Romeo, R., Postrioti, L., Torchio, D., Martino, M., & Malengo, A. (2025). Dynamic calibration of flow meters using reference flow rate profiles generated by injectors. *Measurement*, 256(A), article number 118129. doi: 10.1016/j.measurement.2025.118129.

[30] Roy, A., Kasiviswanathan, K.S., Patidar, S., Adeloye, A.J., Soundharajan, B.S., & Ojha, C.S.P. (2023). A novel physics-aware machine learning-based dynamic error correction model for improving streamflow forecast accuracy. *Water Resources Research*, 59(2), article number e2022WR033318. doi: 10.1029/2022WR033318.

[31] Sapeliuk, R., & Matiko, F. (2025). Analysis of the current state and development trends of computer-aided design systems for flow measurement instruments of fluid media. *Open MenuBulletin of Kyiv Polytechnic Institute. Series Instrument Making*, 69(1), 59-69. doi: 10.20535/1970.69(1).2025.331881.

[32] Shajarian, S. (2025). Towards autonomous network management: AI-driven framework for intelligent log analysis, troubleshooting and documentation. *Proceedings of the AAAI Conference on Artificial Intelligence*, 39(28), 29297-29298. doi: 10.1609/aaai.v39i28.35226.

[33] Shunashu, I.L., & Kaunde, O. (2025). Modelling over-reading correction factors for ultrasonic flow meters in wet gas measurement using advanced regression and machine learning techniques. *SSRN*. doi: 10.2139/ssrn.5220797.

[34] Siqueira de Aquino, G., Martins, R.S., Martins, M.F., & Ramos, R. (2025). An overview of computational fluid dynamics as a tool to support ultrasonic flow measurements. *Metrology*, 5(1), article number 11. doi: 10.3390/metrology5010011.

[35] SOLIDWORKS. (n.d.). Retrieved from https://solidworks.softico.ua/.

[36] Vicente, M., Guarda, J., & Batista, F. (2022). Gutenbrain: An architecture for equipment technical attributes extraction from piping & instrumentation diagrams. In *KDIR 2022 – 14th international conference on knowledge discovery and information retrieval* (pp. 204-211). Valletta: Science and Technology Publications.

[37] Wang, S., Ge, L., Tian, G., Wei, G., Xiao, X., & Zou, M. (2025). Research progress on optimization techniques for electromagnetic flowmeters: A review. *IEEE Sensors Journal*, 25(9), 14557-14574. doi: 10.1109/JSEN.2025.3552894.

[38] Yu, M.-G., & Kim, D.-S. (2025). Low-complexity ultrasonic flowmeter signal processor using peak detector-based envelope detection. *Journal of Sensor and Actuator Networks*, 14(1), article number 12. doi: 10.3390/jsan14010012.

[39] Zhao, N., *et al*. (2021). An empirical investigation of practical log anomaly detection for online service systems. In *Proceedings of the 29th ACM joint meeting on European software engineering conference and symposium on the foundations of software engineering* (pp. 1404-1415). New York: Association for Computing Machinery. doi: 10.1145/3468264.3473933.

Автоматизоване логування помилок у процесі проектування витратомірів: підходи до обробки та аналізу

Ростислав Сапелюк

Аспірант
Національний університет «Львівська політехніка»
79013, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0009-0001-6436-751X

Віталій Роман

Кандидат технічних наук, доцент
Національний університет «Львівська політехніка»
79013, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0002-8546-6752

Анотація. У сучасному проєктуванні витратомірів змінного перепаду тиску актуальним є впровадження надійних систем автоматизованого логування, оскільки традиційні методи журналювання не забезпечують необхідної точності та стабільності під навантаженням. Метою дослідження було обґрунтування та розроблення методичних підходів до автоматизації процесів логування у проєктуванні витратомірів змінного перепаду тиску з урахуванням параметричної оптимізації, скорочення часу локалізації помилок та підвищення точності оцінки невизначеності. Дослідження базувалося на експериментальних вимірюваннях у програмних середовищах SolidWorks 2024 та ANSYS Fluent із використанням інструментарію Elasticsearch і Kibana, а також з подальшою обчислювальною обробкою у MATLAB 2024a. Оцінювання охоплювало метрики точності, повноти, інтегрального показника гармонійного середнього, площі під кривою робочих характеристик, часу до виявлення критичної події, часу до повідомлення інженера, часу до локалізації помилки, середньої похибки розрахунку витрати з бутстреп-аналізом, а також інтегрального індексу ефективності логування. Встановлено, що базове журналювання забезпечує обмежену точність (≈ 71 %) і низьку стабільність (≈ 82,5 % беззбоєвих сесій), тоді як евристичні методи підвищують ефективність до 87,9 %, але залишають значний рівень дублювання подій і втрачають стабільність під навантаженням. Статистична класифікація продемонструвала кращі результати (інтегральна метрика F1-score = 0,81, середня похибка витрати 2,5 %, інтегральний індекс ефективності логування = 0,78), забезпечивши баланс між точністю й швидкодією. Найвищі показники досягнуто у підході з алгоритмами машинного навчання: точність перевищила 91 %, повнота склала понад 87 %, середня похибка розрахунку витрати знизилася до 1,7 %, відновлення причинно-наслідкових зв'язків досягло понад 86 %, а інтегральний індекс ефективності логування становив 0,89. Дисперсійний аналіз та непараметричний тест Краскела-Уолліса підтвердили достовірність відмінностей між підходами. Практичне значення дослідження полягає у визначенні алгоритмів машинного навчання як базового напряму розвитку інтелектуальних систем логування, результати якого можуть бути використані інженерними компаніями, розробниками програмного забезпечення та підприємствами нафтогазової, енергетичної й машинобудівної галузей для підвищення надійності, масштабованості та адаптивності систем проєктування до реальних умов експлуатації

Ключові слова: чисельна гідродинаміка; машинне навчання; діагностика помилок; інтегральний індекс ефективності логування; витратоміри змінного перепаду тиску